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# WRITTEN COMMENTS OF THE OIL SHALE CORPORATION ON THE DRAFT ENVIRONMENTAL STATEMENT PROTOTYPE OIL SH[illegible] LEASING PROGRAM

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COMMENTS

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# WRITTEN COMMENTS
# ON THE
# UNITED STATES DEPARTMENT OF THE INTERIOR
# DRAFT ENVIRONMENTAL STATEMENT
# FOR THE
# PROPOSED PROTOTYPE OIL SHALE LEASING PROGRAM

Submitted By

THE OIL SHALE CORPORATION
1600 Broadway
Denver, Colorado

November 6, 1972

## COMMENTS

1. WATER QUALITY IMPACTS (Volume I, Section III)

The Draft Statement (Volume I, Section III) considers numerous impacts on water quality posed by oil shale development and discusses factors which mitigate those impacts in Section IV. Those considerations might well be expanded to include a recent development of Federal legislation.

With respect to possible water pollution from direct industrial activity, from urban growth, or from indirect industrial and other commercial development that may accompany the development of shale oil production, the recently enacted Federal Water Pollution Control Act Amendments of 1972 could be quite significant. In brief, this Act establishes requirements and provides for enforcement mechanisms that should assure that there will be no significant adverse effect upon water quality. For the first time, this Act imposes strict waste treatment standards upon municipal sewage treatment systems, and it also provides for substantial funding for construction of such systems. In addition, the Act will require the "best practicable" control technology to be applied by July 1977 by every industrial plant discharging water effluents into navigable waters. Beyond that, the bill moves toward a "no-discharge" standard for industrial plants by July 1, 1983.

Furthermore, all industrial plants constructed after October 1972 are to be subject to special standards which will go beyond the requirements applicable to existing plants. These standards are designed to encourage use of the very latest waste control technology in newly constructed plants, and should be applicable to all, or nearly all, industrial establishments operating under the Prototype Oil Shale Leasing Program. In addition, even stricter standards may be applied to industrial plants, where necessary, to ensure attainment of water quality standards or to guarantee that waters will be safe for recreational purposes.

The principal stated objective of the Act is "to restore and maintain the natural chemical, physical, and biological integrity of the Nation's waters". There is certainly good reason to expect that this objective will be achieved. It may also be significant that the beneficial effects of the Act should become operative before there is any significant development that might be attributable to the Prototype Oil Shale Leasing Program.

2. PROJECT RIO BLANCO (Volume II)

The Draft Environmental Statement discusses the possibility of nuclear stimulation of gas reserves as an alternative to oil shale development (Volume II, Pages 124-28; it appears that Page 124 is out of order and should follow Page 125 or 126.) We have studied in some detail the relationship between these two activities, and our

studies and conclusions are attached to these comments as Attachment I. Materials already published in the Plowshare Open File and the Environmental Statements for Project Rio Blanco and Project Wagon Wheel also illuminate the subject.

The seismic motions induced by underground nuclear explosions are so large that surface structures used for oil shale development would be threatened with damage for many miles. Therefore, simultaneous development of nuclear gas stimulation and oil shale in the same small region, such as the Piceance Creek Basin of Colorado, is not a feasible alternative.

Proponents of Project Rio Blanco have suggested that nuclear stimulation of the entire Rio Blanco Unit, using three to five nuclear devices in 140 to 280 wells, could be completed before oil shale development is commenced. Their projections indicate that the delay would be 10 to 20 years. This alternative is not in the National interest for two reasons. First, the seismic energy released from the nuclear blasting would fracture and weaken overlying oil shale and its over-burden. This would make shaft or slope access to, and the mining of, oil shale more expensive, less complete, and perhaps impossible. Second, the energy recoverable from oil shale is on the order of 100 times as great as might be recovered in the form of gas from the same area by nuclear stimulation, and shale oil could be converted to synthetic natural gas

by commercially available processes. Furthermore, it may be the case that the nuclear fuel consumed would, if used instead in a nuclear power plant, be nearly equivalent in energy content to the energy released in the form of gas.

A third alternative is the relocation of nuclear stimulation projects to areas where there would be no interference with oil shale development. As Appendix C in Attachment I shows, there are vast areas of tight gas reservoirs in areas remote from the much smaller oil shale regions. If done in this way, nuclear stimulation and oil shale development could be compatible.

The statement at the top of Page 124, that "Projects Gasbuggy and Rulison are clearly demonstrating that the recovery of natural gas by nuclear explosion stimulation is technically feasible and holds economic promise", is in our view a very optimistic one, which may be attributable to the sponsors of those projects. The reports of those two events indicate that only very modest quantities of gas were released, the major express purpose of the next scheduled test (Project Rio Blanco) is still to determine whether commercial quantities of gas can be released by this means. As to the technical feasibility, the Atomic Energy Commission has said in the Environmental Statement for Project Rio Blanco that hardened nuclear devices for sequential firing must be developed before nuclear stimulation would be feasible on a commercial scale.

Because nuclear stimulation of gas does not offer a logical alternative to oil shale development, the Final Statement should contain an expanded evaluation in Volume I, Section III of the impact of the Prototype Oil Shale Leasing Program upon the proposed Project Rio Blanco and the Rio Blanco Gas Unit. It is suggested that that Section also be expanded to evaluate in more detail the impact upon conventional oil and gas recovery techniques and development of other known minerals.

We are aware that the Department has given lengthy detailed study to the question of conflicts between oil shale development and nuclear gas stimulation and we urge the Department to resolve those conflicts at the earliest possible date. In the event that the Department has not completed its study of those conflicts at the time the Final Statement is prepared, we suggest that the Department include a clear expression of policy in the Final Statement to the effect that if the Department determines that simultaneous development of oil shale and nuclear gas stimulation is incompatible, the Department will not allow nuclear stimulation to proceed in or near the rich oil shale reserves.

3. CLEAN FUEL ADVANTAGES (Volume I, Section IV)

The Draft Statement analysis of mitigating factors or positive advantages arising from oil shale development might be expanded to note the potential effect of clean fuel development.

Among affirmative environmental benefits that might result from the prototype program and the development of a domestic shale oil industry could be the provision of a supply of environmentally ideal fuel for power generation and other purposes in areas that presently experience severe air pollution difficulties. For example, raw shale oil can be refined, by hydrotreating, so as to produce a fuel that emits virtually no sulfur and no ash upon combustion. There is a large and rapidly growing need for such fuel in the southwestern and West Coast States and also in the Mid-West. The oil shale reserves are well located so as to be able to supply any or all of these areas.

The possibilities of realizing these environmentally affirmative benefits would be significantly enhanced by appropriate revisions in the Mandatory Oil Import Program that would assure that shale oil and its products would receive fair and equitable treatment. The principal such changes, which are warranted for a number of reasons in addition to facilitating attainment of environmental benefits of shale oil development, would be to include the initial hydrocarbon liquids (under standard atmospheric conditions) as qualified refinery inputs for purposes of generating import quotas, and to make refiners of shale oil located in the oil shale regions eligible to participate in the low sulfur bonus program on the West Coast to the extent that they might

supply low sulfur oil to be burned as fuel under the conditions of the low sulfur program. Such changes in the oil import regulations should be considered as part of the decision to proceed with the Prototype Oil Shale Leasing Program.

4. ORDER OF LEASE TRACTS (Volume I, Section VIII)

The Draft Statement (Volume I, Page VIII-12) indicates that the selected tracts will be offered for leasing in the order C-a, U-a, W-a, C-b, U-b, W-b. We suggest that in order to maximize the competition of bidding and monetary return to the Government, the tracts should be offered in the order of their interest to bidders, with the most interesting tract being offered first. The public hearings made quite clear the consensus among bidders that the Colorado tracts have the greatest possibility of development, with the Utah and Wyoming tracts following in that order.

The two Colorado tracts designated have been selected for their amenability to particular mining techniques; that is, to open pit mining (Tract C-a) and underground mining (Tract C-b). The overwhelming bulk of oil shale study and development work conducted over the part 15 years has concentrated on underground mining techniques. Those studies, conducted by the Bureau of Mines and by several industrial

companies, have demonstrated the technology and feasibility of room and pillar mining under conditions substantially identical to those used in a commercial operation. Because the technology of underground mining has been amply demonstrated, Tract C-b, which was selected to use that technology, represents the tract which industry can best evaluate and which holds the broadest interest. Therefore, it is suggested that the Colorado tracts be offered in the order C-b, followed by C-a, and the Utah and Wyoming tracts offered thereafter in that order.

The effect of leasing in the order of interest suggested above is that all interested bidders will have an opportunity to bid on each tract as it is offered. If the tract which represented a bidders first choice was the third tract to be offered, that bidder would be reluctant to bid on tracts offered prior to the third tract for fear of obtaining one of those leases and thereby being precluded from bidding on the third lease. If that situation occurs, the competitive bidding will be significantly reduced. By offering the tracts in order of greatest interest, competition and financial return to the Government will be maximized and bidders will be free to bid optimum amounts on each tract.

Furthermore, offering tracts in the order of their interest to bidders should be desirable to the States, since it will have the effect of letting all bidders bid on lands in each State, rather than holding back for a tract in another State. Thus, the tracts in each State will receive the maximum number of bidders.

5. COMMENTS ON LEASE TERMS (Volume III, Section V)

Sections 2(a), 2(q), 4 and 5

The reference to "2(r)" appearing in Sections 2(a), 2(q), 4 and 5 should be changed to read "2(q)".

Section 2(c)(4)(iv)

The provision of Section 2(c)(4)(iv) relating to "extraordinary costs" was intended to compensate Lessees for unusual costs which might be incurred by reason of the unique or unforeseen environmental requirements of the program. However, as written, the provision is ambiguous and might be construed to effectively preclude recovery of such costs. For example, recoverable costs must be "required by the terms of the Mining Plan" and at the same time be outside the "contemplation of the parties". It is difficult to perceive how that situation could occur.

Second, recoverable "extraordinary costs" are limited to those extraordinary costs which "are in excess of the amount of any outstanding bond under Section 5(e)", which Section requires a bond of at least $500 per acre of land affected over a 3-year period. The Program Statement (Page B-2) states that the bond provided under Section 5 is required to be in an amount deemed necessary to meet the anticipated expenses of all requirements of the lease. Therefore, any expenses in excess of that amount would normally not be contemplated and would be considered extraordinary. The existing language of Section 2(c)(4)(iv)

is subject to the interpretation that extraordinary costs alone must total the amount of the Section 5 bond before any credit can be given. Since that clearly was not the intent of the provision, it is suggested that Section 2(c)(4)(iv) be rewritten as follows:

> "(iv) Upon a showing to the satisfaction of the Secretary that compliance with the requirements prescribed in any exploration or mining plan, or amended, supplemental, or partial plan, approved in accordance with the regulations in 43 CFR Part 23, now or hereafter in force, and the requirements of Section 5 hereof, has engendered or will engender extraordinary costs (1) in an amount not within the contemplation of the parties on the effective date of such plan, and (2) which when added to all other costs required by such plan is in excess of the amount of any outstanding bond filed and maintained by the Lessee pursuant to Sub-section 5(e) hereof, the Secretary may, in order to offset such extraordinary costs, adjust the royalties that would otherwise become due and payable thereafter under Sub-sections 2(c) or 2(d) by allowing a credit against those royalties in such amount, and for such time, as he determines are warranted in the circumstances. In general, the Lessor agrees that extraordinary costs in excess of the amount of any outstanding bond under Section 5 shall be allowed in cases where Lessee has demonstrated due diligence in complying with environmental requirements and the extraordinary costs could not reasonably be avoided."

New Section 2(s)

The Program Statement for the Prototype Oil Shale Leasing Program indicates that the program will recognize the proprietary rights of Lessees with respect to processes and related confidential technical information. Unfortunately, the lease terms make no express provision for such protection and the language of two provisions in the lease raises some question as to whether such protection will exist. The

Oil Shale Corporation owns extensive process technical information which has been developed at the expense of substantial time and money. Before committing that technology to an operational lease, TOSCO would want an express provision in the lease protecting the confidential nature of such information and clearly establishing the rights of the parties to such proprietary information. Such provisions are common in business arrangements, and we suggest that the following language is one acceptable form which might be added as a new section of the lease:

"(s) Protection of Proprietary Information

It is expected that development of the leasehold will utilize patented processes and proprietary confidential technical information owned or licensed by Lessee. With respect to such confidential technical information, whether developed in connection with this lease or otherwise, Lessor agrees (1) that such information shall be exempt from the inspection rights granted under Section 2(h), except that upon written request by Lessor, Lessee shall disclose to the Lessor limited confidential technical information to the extent necessary (a) to determine royalty and production payments, and (b) to assess compliance with the environmental terms of the lease. With respect to such disclosures of confidential information by Lessee, Lessor agrees (1) it will not disclose any such confidential information to third parties, (2) will not copy or reproduce such information, (3) will not use such information in any way which will violate its proprietary nature, and (4) shall return such information to Lessee upon request.

This lease, and any activities thereunder, shall in no way be construed to grant a license, permit, or other right of use or ownership to Lessor, or other persons, of the patented processes or confidential technical information used or developed by Lessee in connection with this lease.

Furthermore, it is expressly agreed that the right to purchase plants and equipment granted to Lessor under Section 7 of this lease does not include a right to use or operate any processes, equipment or plants containing patented or confidential technical information, nor to disclose such information to third parties."

Section 2(h)

In order to conform the lease terms to the provisions of the new clause (Section 2(s)), it is suggested that the period at the end of Section 2(h) be changed to a semi-colon and the words "except as otherwise provided in Section 2(s)" be added.

6. COMMENTS ON STIPULATIONS (Volume III, Section V)

Section 1(A)

It is suggested that the language of Section 1(A) is broader than was reasonably intended and imposes an undue burden on Lessee. A similar provision fixing the responsibility of Lessor appears in Section 1(E)(1) below and it is suggested that the standard of liability should be the same for both parties. Therefore, it is recommended that the following changes be made:

After the word "Stipulations" appearing in the sixth line of the section, insert the words "when such persons are acting within the scope of their employment or are concerned with the Lessee's operations or the Lessee's compliance with the lease".

After the word "sub-contract" appearing in the ninth line of the section, insert the words "under this agreement".

After the word "shall" appearing in the twelfth line of the section, insert the words "when acting pursuant to such agreements".

Section 1(E)(1)

For the reasons stated in the comment on Section 1(A) above, the word "authority" and the period at the end of the sub-section should be deleted and the following words inserted in lieu thereof, "employment or are concerned with the Lessee's operations or the Lessee's compliance with the lease".

Section 2(B)

It is suggested that this provision should be clarified by inserting after the word "supervisor" appearing in the fifth line of the section, the following sentence, "In general, plant sites, mine sites, disposal areas and other operational sites will not be open to the general public."

Section 2(E)

The language of this provision would be clarified by adding at the end of the parenthetical expression in the first and second lines of the section, the words "by order of the Mining Supervisor", and

by adding after the word "pipelines" appearing in the third line of the section, the words "on the leased lands".

Section 2(J)

It would be appropriate to insert after the word "fence" appearing in the third line of the section, the words "or other suitable barrier".

Section 6(A)

This provision would be clarified by adding, after the word "investigation" appearing in the second line of the section, the words "of leased areas to be used for processing, mining, or disposal operations".

Section 8(B)

This provision might be made more appropriate by adding the word "reasonable" after the word "every" appearing in the first line of the section.

Section 13(C)

This provision should be clarified by inserting after the word "for" appearing in the second line of the section, the words "processing, mining, disposal and other operations under the lease and for"...

ATTACHMENT I

# THE INCOMPATIBILITY OF NUCLEAR GAS STIMULATION WITH OIL SHALE DEVELOPMENT IN THE PICEANCE CREEK BASIN, COLORADO

THE OIL SHALE CORPORATION

July, 1972

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C. The output of only two small commercial oil shale plants is equivalent to 116 per cent of the energy which the sponsors predict may be produced over 20 years by the entire Unit; and the shale oil produced could be converted by existing processes to synthetic natural gas equivalent to 98 per cent of the volume of such natural gas. Page 13

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SUMMARY

## SUMMARY

The Oil Shale Corporation (TOSCO) reluctantly but firmly opposes the execution of Project Rio Blanco and the nuclear development of the Rio Blanco Unit.

TOSCO's reluctance to be in opposition arises out of its fundamental support for the prompt development of nuclear gas stimulation technology to aid in meeting increasingly disturbing United States energy deficits. However, as the President's Energy Message directed, that technology and the development of shale oil production can and should be pursued simultaneously.

Whereas the oil shale deposits of the Piceance Basin are unique, the gas sands of the Rio Blanco Unit are not. Their occurence is widespread, and another project, Wagon Wheel, has already been announced in an area larger in gas production potential and without competing resources. No unique technological advantage or expected gain from the Project Rio Blanco site or the Unit has been suggested by the sponsors to justify the material delays in oil shale development, or the material risk of injury to the recovery of oil shale and related minerals, that would result from the proposed nuclear development of the Rio Blanco Unit.

The critical error of the Project Sponsors is their assumption

that commercial shale oil development is at least a decade or more away.

In fact, after project expenditures of more than $95 million, and development labors occupying nearly 17 years, Colony Development Operation expects to announce construction of the first commercial shale oil facility within a few months, probably by year-end. Production would commence in 1976 at the level of 47,500 barrels per day of finished liquid petroleum products. TOSCO is a member of the Colony group; Atlantic Richfield Company is the Operator.

Similarly, the Sponsors ignore the Federal Oil Shale Leasing Program, launched at Presidential direction after painstaking planning for orderly development. The Rio Blanco Unit would render nearly valueless for at least a decade the Colorado leaseholds scheduled for offering by competitive bidding in December of this year.

The text and appendices which follow set out the reasons for TOSCO's opposition in detail.

Divorced from their inherent complexities, three reasons are paramount:

1. The blast effects predicted by the AEC from the detonations necessary to the development of the Rio Blanco Unit would subject major industrial facilities on approximately

95 per cent of the entire oil shale reserves of the Piceance Basin to stresses which are beyond existing design experience. Development of the Rio Blanco Unit therefore would require postponement for as much as a decade or more of the now imminent commercial production of shale oil.

2. Shale oil production, expected to commence at approximately 47, 500 barrels per calendar day of finished petroleum products in 1976, can thereafter be increased to major production levels as fast as relevant national policies dictate. Only two plants of the relatively modest scale of the first proposed installation can produce petroleum liquids suitable for conversion to Substitute Natural Gas in an amount equal to the entire daily gas production anticipated from a fully successful Rio Blanco Unit. By 1980 therefore the amount of hydrocarbon energy available from development of Piceance Basin oil shale deposits would exceed the Rio Blanco Unit projections many fold, and the rate would increase thereafter.

3. The proposed nuclear blasting at the richest center of the Piceance Basin oil shale deposits will significantly increase the difficulty and cost of recovery of oil shale minerals throughout the area. AEC data indicate spalling of upper layers of overlying rock; and subsequent mine access through that material will unquestionably be more costly and hazardous. Less

definitive data suggest that mining of oil shale horizons above the blasts may be rendered more costly or impossible by a similar spalling effect. The Sponsors of the Project agree that the blasts will cause movement along existing faults up to 7000 feet away. Such movements will reduce the strength of the rock and result in increased mining costs and reduced resource recovery. Such economic and physical losses of reserves could erase the net energy gain from gas production upon which Project Rio Blanco is predicated, and which is the manifest purpose of the President's program.

The delays and risks to far larger energy resource development in the Piceance Basin which are inherent in the proposed Rio Blanco Project are not justified by any gain to a nuclear stimulation experiment situated there. The technological development effort should undoubtedly be made promptly at wisely selected sites. TOSCO will support such an effort by any means reasonably available to it.

I. THE TOSCO TECHNOLOGY FOR OIL SHALE PRODUCTION IS NOW FULLY TESTED AND READY: THE PROJECT INVESTMENT TO DATE IS MORE THAN $95,000,000; FINAL DECISION ON COMMERCIAL PLANT CONSTRUCTION ON ITS OWN RESERVES BY COLONY DEVELOPMENT OPERATION IS SCHEDULED BEFORE YEAR-END; AND COMMERCIAL PRODUCTION OF SHALE OIL PRODUCTS IS PLANNED FOR 1976, YEARS IN ADVANCE OF THE SUGGESTED COMPLETION DATE OF RIO BLANCO.

A. Field evaluation of the TOSCO technology at pilot plant and semi-works plant scales was successfully completed in April, 1972, and forward planning by Colony Development Operation calls for commercial plant commitment by year-end and initial production in 1976 after three years of construction commencing in 1973.

The Oil Shale Corporation was organized in 1955 in order to perfect and commercialize its process for the extraction of hydrocarbons from oil shale. This remains its paramount corporate goal. In 1964, after successful demonstration of the TOSCO II retorting process in a 24 ton per day pilot plant, TOSCO entered into a joint venture with The Standard Oil Company (Ohio) and The Cleveland-Cliffs Iron Company. The venture, which was joined in 1969 by Atlantic Richfield Company as Operator and which is now known as Colony Development Operation, built in 1965 and operated until April of this year a 1,000 ton per day semi-works plant and underground mine at Parachute Creek, Colorado. See Figure 1. 1/

1/ All figures are found in Appendix A.

In April, 1972, the Operator, Atlantic Richfield Company, announced the "successful establishment by field operations both of the technology and the required environmental safeguards."

The Ralph M. Parsons Company and others have carried out design, engineering studies, and cost estimates for a commercial plant, at a cost to Colony of more than $1 million, and the final engineering program is now continuing and accelerating. The projected first commercial plant is designed to produce 47,500 BPCD of hydrotreated sulfur-free distillate product and will cost more than $200 million to build.

The hydrotreated shale oil distillate product is a highly desirable fuel from an environmental viewpoint because it is low in nitrogen and essentially free of sulfur and ash. The lighter fraction of the product is also an ideal feedstock for synthetic natural gas production, and with appropriate conventional treatment the entire plant product could be so utilized. The distillate product is of particular interest to utility consumers because of its quality, and because it is a secure, long-term, domestic source of supply. These analyses and conclusions are based not only on work conducted by and for Colony Development Operation, but also on the progress of product disposition negotiations currently in progress.

Final project evaluations antecedent to commercial plant commitment are expected to be successfully completed before year-end. The construction timetable thereafter provides 36 months, including contingencies, to on-stream operation in 1976.

B. TOSCO and its co-venturers have expended more than $95,000,000 of their own funds to reach commercial readiness; more than $63 million in technological development; and more than $31 million in acquisition of reserves suitable for development.

The expenditures for technology include construction and operation of TOSCO's 24 ton per day pilot plant; construction and operation of the 1,000 ton per day semi-works plant, including development and demonstration of environmental protection measures; mining of more than one million tons of shale to develop and test at full scale the techniques to be used commercially; bench scale investigation of shale oil upgrading to provide data for commercial design; development and testing of environmentally satisfactory methods for processed shale disposal, including revegetation procedures; and preparation of commercial project feasibility studies, including detailed design work, capital and operating cost estimates, and market projections.

Appendix B provides further information on the above expenditures as well as on the expenditures of more than $31 million on reserves acquisition. This latter expenditure includes only money spent by TOSCO and the oil shale joint venture in which it is a participant. It does not include expenditures by the other venture participants outside the venture, or expenditures by other companies which have invested substantially in reserves and in related technology, particularly for shale oil refining.

C. The AEC states only that the first increment of gas production from the Rio Blanco Unit is "possible" in 1977, and that subsequent full field development will occur on an unspecified schedule depending, inter alia, on enabling Congressional action.

The Environmental Statement (pages 2-10 and 2-13) notes that development of the Rio Blanco Unit is projected in three separate phases of which the initial Rio Blanco shot is Phase I. Phase II is anticipated to comprise detonation of three to five explosives per well in four to six wells and is expected to be completed in 1975 or early 1976. Phase III is stimulation of 20 to 60 additional wells, enough to justify construction of a pipeline and production of some gas for sale.

The Environmental Statement notes that a "possible" schedule for such production is mid-1977. The next step, full field development, would comprise a series of multi-well stimulations some six months to a year apart.

The estimated time of completion of full field development is not given in the Statement. However, Mr. Fred Evans, President of Equity Oil Company stated at the AEC's Meeker, Colorado hearing on March 24, 1972 (Transcript page 52):

> If Project Rio Blanco is a technical and economic success, we feel that it is not unreasonable to project full field development of the Rio Blanco Unit in a period of ten to twelve years....

The Environmental Statement acknowledges that additional Impact Statements must be prepared prior to each new phase of the program, and notes that enabling federal legislation is needed before the explosives and services necessary for commercial development can be provided. Mr. Evans' estimate of ten to twelve years for field development may be optimistic.

## II. THE RECOVERABLE SHALE OIL AND OTHER MINERAL VALUES OF THE PICEANCE BASIN ARE HUNDREDS OF TIMES LARGER AND MORE VALUABLE THAN THE VALUE OF THE ESTIMATED GAS PRODUCTION THAT MIGHT RESULT FROM THE RIO BLANCO UNIT.

### A. The Piceance Creek Basin oil shale deposit which is the world's largest known hydrocarbon resource, containing more than 450 billion barrels of reserves of good quality, is found 25 per cent within the confines of he Rio Blanco Unit; and 95 per cent of the entire reserve is found in the Unit and within ten miles of the Unit.

The Piceance Creek Basin, outlined in brown on the map in Figure 2, contains the largest and richest known oil shale deposit and hydrocarbon reserve in the world. According to the Geological Survey,[2/] the Basin contains the equivalent of 450 billion barrels of oil in oil shale averaging 25 gallons per ton or more. Assuming only a 50 per cent recovery factor, (see Appendix C), this is more than 23 times the size of the reserves in the Alaskan North Slope Field estimated at 9.6 billion barrels.[3/] It is 5.8 times the size of the Nation's proved conventional crude oil reserves, including the North Slope field,[4/]

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2/ D. C. Duncan and V. C. Swanson, Organic Rich Shale of the United States and World Land Areas, Geological Survey Circular 523 (1965)

3/ National Gas Supply and Demand 1971 - 1990, Federal Power Commission Staff Report, Bureau of Natural Gas (1972).

4/ See Reserves of Crude Oil and Natural Gas Liquids and Natural Gas in the U.S. and Canada and U.S. Productive Capacity as of December 31, 1971, vol. 26, American Petroleum Institute (May 1972).

and is equivalent to the amount of petroleum which the Department of the Interior estimates will be consumed in the United States in the years from 1973 to 2000.[5/]

The thickest deposits of the rich oil shale are in the central portion of the Basin where the Rio Blanco Unit is located. See Figure 3. Consequently, disproportionately large percentages of the total reserves are concentrated in and near the Rio Blanco Unit.

The following table sets forth the portions of the 1302 square miles within the Basin and the portions of the 225 million barrels of recoverable oil shale in the Basin which lie within the Unit and within the areas described by radii of 5, 7, 10, 15, and 20 miles from the Unit boundaries.

| Distance from Unit Boundary (Miles) | Area: Area Within the Zone (Square Miles) | Area: Per cent of Total Basin Area | Recoverable Oil Shale Reserves[6/]: Billions of Bbls. | Recoverable Oil Shale Reserves[6/]: Per Cent of Total in Basin |
|---|---|---|---|---|
| 0 | 145 | 11 | 55.5 | 25 |
| 5 | 554 | 43 | 170 | 75 |
| 7 | 714 | 55 | 190 | 84 |
| 10 | 944 | 73 | 215 | 95 |
| 15 | 1213 | 93 | 220 | 98 |
| 20 | 1302 | 100 | 225 | 100 |

5/ United States Energy - A Summary Review, Department of Interior (January 1972).

6/ Assumes 50 per cent recovery of oil shale averaging 25 gallons per ton. See Figure 3 which is derived from U.S. Bureau of Mines R.I. - 7051.

B. At only 50 per cent recovery of good quality reserves, the energy value of the Piceance Basin shale oil is some 380 times greater than the energy value of the estimated 20 year production of gas from the Rio Blanco Unit; on a similar basis the energy from the oil shale within the Rio Blanco Unit is about 100 times the energy of the estimated gas production.

As noted above and supported in Appendix C, the reserves of oil shale in the Piceance Creek Basin total approximately 450 billion barrels of oil in oil shale averaging 25 gallons per ton. The average energy content of shale oil is $6 \times 10^6$ Btu per barrel. Therefore, assuming a 50 per cent recovery factor, the recoverable oil shale energy in the Basin is $1,350 \times 10^{15}$ Btu.

CER has projected that full field development of the Rio Blanco Unit, using multiple nuclear bombs in 140 to 280 or more wells, could produce 3.48 trillion standard cubic feet (SCF) of natural gas over 20 years. CER Geonuclear Corporation, Economics of Nuclear Stimulation at 3, October 29, 1970; Environmental Statement at 2-10. Natural gas having an energy content of approximately 1000 Btu per SCF, the total energy which might be developed in 20 years from the whole Rio Blanco Unit is $3.48 \times 10^{15}$ Btu. Hence, the recoverable oil shale reserves in the Basin contain about 388 times as much energy as the gas which might be recovered from the Rio Blanco Unit in 20 years. Since 25 per cent of the oil shale reserves lie within the Unit, the ratio for the energy of these reserves to the energy of the gas is about 100 to 1.

These ratios would be further unbalanced if the projected gas energy to be made available were reduced to the net amount of energy production available after deduction of the nuclear fuel consumed. The net amount of energy is not revealed in the Environmental Statement, and is apparently regarded by the AEC as classified information. Environmental Statement at F-17 and 9-7.

C. The output of only two small commercial oil shale plants is equivalent to 116 per cent of the energy which the sponsors predict may be produced over 20 years by the entire Unit; and the shale oil produced could be converted by existing processes to synthetic natural gas equivalent to 98 per cent of the volume of such natural gas.

The 3.48 trillion SCF of natural gas which CER has predicted could be produced over 20 years amounts to an average of about 477 million SCF per day. By comparison, if only the 22,700 barrels per calendar day (BPCD) of hydrotreated naphtha expected to be produced by Colony's first small commercial plant were converted to synthetic natural gas (SNG), the output would be 114 million SCF per day; and if Colony elected to make its product slate entirely naphtha, again using conventional processes, the resulting 46,290 BPCD of naphtha would produce 233 million SCF per day of SNG. Thus the total gas output of the entire Rio Blanco Unit at full development is about the same

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as could be realized by converting to SNG the liquid output of two modest-scale commercial shale oil plants, each the size of the first Colony unit.

Perhaps more meaningful is a comparison between recoverable gas and recoverable shale oil on a Btu basis. Natural gas has an energy content of approximately 1000 Btu per SCF. Therefore, 477 million SCF per day is equivalent to 477 billion Btu per day. The planned first oil shale plant is designed to produce 47,500 BPCD of finished liquid products having an average energy value of 5.8 millionBtu per barrel, or 276 billion Btu per day. Thus, the net daily energy output of the first commercial oil shale plant in 1976 will be equivalent to the energy in 58 per cent of all the gas which might be produced daily by the entire Rio Blanco Unit, after completion of full field development, perhaps in 1985. (This comparison makes no deduction for consumption of nuclear energy to stimulate the gas.)

D. Major deposits of nahcolite (useful for removal of $SO_2$ from stack gases) and Dawsonite constituting the nation's largest deposit of aluminum ore are also threatened with injury and delay in development.

In addition to the potential loss of recoverable energy from oil shale, it should be noted that the recovery of two important

minerals associated with the oil shale is also threatened. Nahcolite, a form of sodium bicarbonate, is potentially useful in systems for removal of $SO_2$ from stack gases. Although the complete distribution of Dawsonitic oil shale is unknown, data from one drill hole indicate that Dawsonitic aluminum in one square mile exceeds that in the total Bauxite reserves of the United States.[7/] As the maps in Figures 4 and 5 illustrate, these mineral deposits are heavily concentrated in and near the Rio Blanco Unit.

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7/ R. J. Hite and J. R. Dyni, Potential Resources of Dawsonite and Nahcolite in the Piceance Creek Basin - Northwest Colorado, 62 Colorado School of Mines Quart. 25 (1967). (The authors are employees of the U.S. Geological Survey.)

III. SO LONG AS THE THREAT OF NUCLEAR BLASTING IN THE RIO BLANCO UNIT CONTINUES, IT MATERIALLY IMPAIRS OR PREVENTS INVESTMENT IN ENGINEERING, CONSTRUCTION, AND OPERATION OF COMMERCIAL OIL SHALE RETORTS AND UNDERGROUND MINES ANYWHERE IN THE PICEANCE CREEK BASIN, EXCEPT PERHAPS ON THE FRINGES OF THE BASIN, AND THEN ONLY WITH GREAT UNCERTAINTY AND SEVERELY INCREASED COSTS.

The Environmental Statement acknowledges, at 9-6, that nuclear explosions for gas stimulation are incompatible with room and pillar mining and the presence of large oil shale retorting equipment in "close proximity." The term "close proximity" is not defined although it is clear that the incompatibility referred to results from the seismic forces caused by nuclear detonations. We must therefore turn briefly to available information on the magnitude and effects of the seismic forces so as to quantify the extent of the incompatibility.

Normal Seismic Design Standards. In discussing the effects of the seismic forces from the proposed blasts, it is relevant to begin with a brief review of design standards for coping with natural earthquakes:

1. The Piceance Basin of Colorado is only feebly active with respect to natural earthquakes and, apart from nuclear disturbances, structures in the area would normally be designed for Zone 1 of the Uniform Building Code (UBC). The peak horizontal component of the seismic acceleration can be expected to 0.1 g or less in this zone.

2. In areas known to be seismically active as, for example, the Los Angeles area, buildings and structures are frequently designed to avoid collapse under horizontal vector accelerations of 0.3 g.

3. In special circumstances, designs have been prepared to withstand a peak horizontal vector of 0.5 g. An example of a design for 0.5 g is the nuclear power facility of Southern California Edison at San Onofre, California, a seismically active area.

4. Although we have discussed the subject with experts in the field including major engineering contractors, we are unaware of any industrial processing facility that has been designed for a seismic acceleration above 0.5 g.

In design of structures against seismic forces, other factors in addition to peak accelerations are important, including the frequency spectra of the wave and the natural frequency of the structure. Our consultants (Dames & Moore) have informed us that, for the dominant forces, the nuclear wave is of considerably higher frequency than normally encountered with natural earthquakes. This difference tends to make the nuclear blast wave less sèvere for flexible structures than a natural seismic wave of equal force, but more severe for semi-rigid structures. The high frequency nature of the nuclear waves is detrimental to oil shale development

because of the prevalence of costly semi-rigid structures in oil shale processing facilities.

Area Affected by Seismic Forces. The Environmental Statement, at 3-3 et seq., provides information on seismic forces resulting from a detonation of the size and type planned for Project Rio Blanco. Figure 3-1 presents the AEC's predicted values of the peak resultant vector accelerations at various distances from the explosion. This graph also shows the uncertainty of the predictions in terms of standard error, $\sigma$.

Dames & Moore, whose Report is included as Appendix D, advise that horizontal vectors can be derived from peak resultant vectors by using the factor 0.707. Peak resultant vector accelerations derived from Figure 3-1 are presented in columns 1 through 3 in the following table. In columns 4 and 5 the resultant vectors are converted to horizontal vectors.

| | Peak Resultant Vector Acceleration (g) | | Peak Horizontal Vector Acceleration (g) | |
|---|---|---|---|---|
| Distance Miles | Predicted Mean Value | Mean + 1 $\sigma$ | Predicted Mean Value | Mean + 1 $\sigma$ |
| 3 | 2.5 | 5.5 | 1.75 | 3.9 |
| 5 | 0.85 | 1.9 | .60 | 1.3 |
| 7 | 0.41 | 0.9 | .29 | .63 |
| 10 | 0.18 | 0.4 | .13 | .28 |
| 15 | 0.08 | 0.18 | .06 | .13 |

From conventional statistical analysis, it can be expected that the seismic force will exceed the mean prediction in 50 per cent of the events and the mean-plus,one sigma value in 16 per cent of the events.

Because industry has not been called upon to design its facilities to withstand man-made seismic forces, there are no design standards derived from analysis of cost and risk which establish the confidence level above the mean which should be selected. However, from consideration of other criteria used for design against catastrophic events, such as record floods, it is apparent that oil shale processing facilities costing more than $200 million would require more than 99 per cent certainty that the aggregate effect of scheduled nuclear blasts to which the plant will be exposed would not result in a seismic force exceeding the design limit. See Appendix D, paragraph 5.

It is not clear that the Environmental Statement provides sufficient information to determine predicted maximum seismic forces with confidence levels of 99 per cent or higher. However, if normal statistical rules are applicable to the data presented, one could be 97.5 per cent confident that the forces from an actual event would not exceed the mean plus two sigma. (The Environmental Statement filed by AEC in connection with Project Wagon Wheel shows plus and minus two sigma lines on the plots of similar seismic data predictions for that event.)

For purposes of this further analysis, we have selected the 97.5 per cent confidence level for determing the magnitude of seismic forces that must be dealt with in designing structures at various distances from ground zero. It must be emphasized that this selection is made for the purpose of accommodating our analyses to the data available. The commercial design of a $200 million structure would necessarily be based on a much higher confidence level, particularly in view of the number of blasts which would have to be anticipated.

The following table shows the 97.5 per cent confidence level values for predicted peak horizontal vector accelerations at selected distances from ground zero.

| Distance (Miles) | Peak Horizontal Acceleration (g) |
|---|---|
| 3 | 8 |
| 5 | 3 |
| 7 | 1.4 |
| 10 | 0.6 |
| 15 | 0.3 |
| 20 | 0.16 |

The table shows that at ten miles one would have to design for horizontal accelerations of 0.6 g , even though 0.5 g appears to be the upper limit of current practice for industrial processing facilities. At 15 miles one would have to use

strengthened, and more expensive, structures in order to withstand 0.3 g. Even at 20 miles normal design standards could not be used. If the foregoing table is read in connection with the map in Figure 6, it is apparent that nuclear blasts in the Rio Blanco Unit will produce seismic accelerations greater than normal design values throughout the entire Piceance Creek Basin. The following table shows the actual percentage of oil shale reserves within each "seismic risk zone" in Figure 6.

| Distance (Miles) | Peak Horizontal Acceleration at 97.5% Confidence Level (g) | Per cent of Oil Shale Reserves in Basin 8/ | |
|---|---|---|---|
| | | Within Interval | Cumulative Total |
| Within Unit | 10 | 25 | 25 |
| 0-5 | 3 | 50 | 75 |
| 5-7 | 1.4-3 | 9 | 84 |
| 7-10 | 0.6-1.4 | 11 | 95 |
| 10-15 | 0.3-0.6 | 3 | 98 |
| 15-20 | 0.16-0.3 | 2 | 100 |

Effect of Seismic Forces on Design of Retorting Facilities.

Dames & Moore and The Ralph M. Parsons Company, have provided us with quantitative information on the added costs of designing to withstand a peak horizontal vector of 0.6 g compared to normal design for Zone 1 of the UBC. Because time available for the study was short, it was restricted to this single case.

8/ The reserve estimates were made by TOSCO from data presented in Bureau of Mines R.I. 7051 and are subject to normal uncertainties in calculating reserves from isopach maps. Reserve estimates are uncertain in the 15 to 20 mile zone because of lack of basic data. The two per cent value shown for this area may be high.

Using data from the Environmental Statement, Dames & Moore provided information on the spectral frequency of the nuclear blast seismic wave. For five different structures present in an oil shale processing facility, Parsons computed the costs of designs to comply with Zone 1 of the UBC and the costs of designs to withstand the seismic wave prescribed by Dames & Moore.

Because of a time limit, the study included only relatively simple structures which could be rapidly analyzed and their costs determined. The five structures and the results of the analysis are described below:

1. The commercial plant design already prepared by Parsons includes a tank to hold water used for decoking in the delayed coking unit. The Parsons work shows that the cost of this tank will be increased 100 per cent from $22,000 to $44,000 if it must be designed against a seismic acceleration of 0.6 g instead of in accordance with the Zone 1 requirement of the UBC.

2. The analysis included a pipe support structure, one typical of a large number of such structures used in the oil processing complex. The results showed that the cost of this structure would be increased by 17 per cent if it had to be designed against the peak acceleration of 0.6 g.

3. Examination of the design of a 143-foot high bent included in the commercial design to support a belt conveyor carrying crushed shale showed that, because of existing provision against wind load, the design will withstand the 0.6 g seismic acceleration.

The detailed study of this structure shows that because of its flexibility, it was only modestly affected by the high frequency nuclear shock wave.

4. A fourth analysis was of the building and structure designed to house centrifuges in the oil recovery area. Allowance for nuclear seismic activity of 0.6 g causes the concrete needed for this structure to be increased in cost from $44,000 to $68,000. The total cost, including the building, is increased 37 per cent from $64,000 to $88,000.

5. The remaining item analyzed was the foundation for the large fractionating column used to condense the retort vapor product and to separate it into its various components. The 0.6 g acceleration vector caused a 115 per cent increase in the cost of the foundation, from $60,500 to $131,200.

In making the analyses shown above, Parsons designed structures exactly for the high seismic force at the structural yield point - that is, without any safety factor. For the base design for Zone 1 of the UBC, the design included conventional safety factors of approximately 33 per cent.

Conclusions. The analysis by Parsons was limited to the items noted above and we cannot, from that limited information, make a definitive judgment as to the total added cost involved in designing the plant for a seismic force of 0.6 g. However, it is apparent that the cost increment for a $200 million plant would be very large and we believe that the term "close proximity" must include at least those areas exposed to a peak horizontal seismic acceleration of 0.6 g. It should be remembered that engineering companies have little or no experience with designs for such stresses.

In the face of full field development of the Rio Blanco Unit, the selected confidence level of 97.5 per cent would require that retorting facilities be designed for a peak horizontal acceleration of 0.6 g at distances as far as ten miles from the boundaries of the Rio Blanco Unit. The ten-mile limit zone which would be condemned for construction of oil shale facilities by field development of the Rio Blanco Unit contains some 95 per cent of the Basin's oil shale reserves. It includes all of the land which Colony

will use for the first commercial oil shale plant. It also includes high grade properties -- all candidates for early oil shale development -- belonging to Union Oil Company of California, Chevron Oil Company, Getty Oil Company, and others.

The conclusion that the reserves within ten miles of the Rio Blanco Unit are precluded from oil shale development so long as the threat of nuclear explosions in the Rio Blanco Unit remains should not be regarded as acknowledgement that the plant construction and operation can proceed at further distance from the Unit. In the zone ten to 20 miles from the Unit, plants and mines would have to be designed to withstand seismic accelerations of 0.16 to 0.6 g at the 97.5 per cent confidence level and to more than twice these values to reach a confidence level in the range of 99.9 per cent. Thus, if a 99.9 per cent confidence level were employed, further extrapolation of the data in the Environmental Statement would indicate that the 0.6 g zone would extend to more than 15 miles from the Unit and would forestall development on more than 98 per cent of the oil shale reserves in the Basin.

## IV. NUCLEAR BLASTING WILL INCREASE THE COST OF UNDERGROUND MINING OF OIL SHALE IN THE LARGE DEPOSITS WHICH OVERLIE THE BLAST SITE AND WILL CREATE A MATERIAL RISK THAT THE QUANTITY OF OIL SHALE RECOVERABLE FROM SUCH DEPOSITS WILL BE REDUCED.

### A. Mining costs and recovery factors are adversely affected by increasing the frequency or reducing the strength of fractures.

Because high overburden to oil shale ratios throughout most of the Basin would make surface mining uneconomic, it is probable that at least for the foreseeable future, oil shale will be mined predominantly by the room and pillar method, or some other underground mining technique. Colony has spent approximately $2 million developing the room and pillar method, and will use it with the first commercial plant. The Bureau of Mines and Mobil Oil Corporation have used the room and pillar method at Anvil Points, and Union Oil Company of California has also done field development work with this technique. TOSCO is not aware of any field development work in oil shale mining employing a different method.

The oil shale in the Colony mine is fractured at intervals averaging three to four feet, and the core hole data indicate that oil shale throughout the Piceance Creek Basin is also highly fractured.[9/] Figures 7, 8 and 9 are photographs illustrating jointing in the Colony mine. Such

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9/ The term "fractures" includes all breaks or discontinuities in the rock. If movement along the fracture has occurred, it is called a "fault." "Joints" are fractures where significant movement has not occurred. "Bedding planes" are depositional boundaries which may or may not be consolidated. If not consolidated, their structural integrity is comparable to joint surfaces.

fractures are weaknesses in the rock and strongly influence the behavior of the rock in mining operations. For example, high-angle fractures, such as those in Figure 8, tend to cause pillar failure by shearing along the plane of the fracture. Figure 9 shows a pillar which has been through-bolted to prevent such failure.

In the room and pillar method, large pillars of oil shale are left in place to support the roof. The feasibility and cost of the room and pillar mining method are closely related to the strength of these pillars and the competence of the roof. Where weak or highly fractured rock is found, larger pillars and smaller rooms must be used, reducing the amount of the oil shale that can be recovered and increasing mining costs, because the use of large, productive equipment is restricted. Expensive rock-bolting programs and water control procedures may also be required.

Oftentimes fractures have been "recemented" by deposition of calcite or other water soluble material. See Figures 7 and 9. Such joints are stronger than uncemented joints, which may have no tensile strength and very low shear strength, but they are usually much weaker than the rock itself. If movement, transient or permanent, occurs along a recemented joint, the "cement" is weakened or broken and the fracture thereafter will have lower tensile and shear strengths. This fact has been overlooked in the Environmental Statement, where it is asserted, at 5-12, that nuclear blasts will have no effect on mineability, even though movement along faults is predicted to occur as far as 7000

feet from the blast point. (The AEC seemed to be considering only the possibility that such movements would alter permeability.) CER has acknowledged that "the Rio Blanco detonation may cause some movement along present fractures." Executive Summary - Project Rio Blanco at 3.

Because of the obvious importance of fracture frequency and strength to rock mechanics, much work has been done to try to relate such data directly to mine dimensions and costs. These efforts have not been successful. It is clear that increasing the frequency of fractures or reducing their strength does tend to increase mining costs and reduce resource recovery, but mining engineers must use such information in a qualitative and intuitive way only. Appendix E treats this complex subject in somewhat more detail.

The extent of fracturing above the mining horizon in and near the Rio Blanco Unit is also important because access to those mines must be gained by inclined adits or vertical shafts from the surface. If the overburden is too weak to support itself, reinforced concrete is required to make the adits and ventilation shafts secure.

B. Nuclear blasting will increase the frequency of fractures in and above the oil shale and will weaken existing fractures by causing movement.

The industrial sponsors of Project Rio Blanco and the AEC have made several important errors in their analysis of the seismic effects of nuclear blasting on the overlying oil shale.

Movement Along Fractures. The first error is the assumption that the oil shale should be regarded as undamaged if no new fractures

are created. Environmental Statement at 5-12. Mere transient movement along existing fractures, which the sponsors concede may occur along faults as far as 7000 feet from the blast (ibid.), weakens fractures and decreases mineability. For the reasons set forth in Appendix E, the science of rock mechanics is not sufficiently precise to permit a prediction as to the magnitude of this effect, even if accurate data as to the number of fractures so weakened could be obtained. But if only one percent of the oil shale is made unmineable, in the section or half-section in which the blast occurs, the blast will have made unavailable as much hydrocarbon energy as it releases.

Near-Surface Spalling. The second error is the failure to recognize that spalling of the surface rock to depths of several hundred feet will substantially increase the costs of mine access. TOSCO's Mining Department has estimated that the additional costs of developing a mine for a 66,000 ton per day oil shale plant (the size of Colony's proposed commercial plant) under a surface spalled to a depth of only 300 feet may be the order of magnitude of $8 million.

Oil Shale Spalling. A third error concerns the method of predicting maximum spall depth. The AEC estimated in the Environmental Statement, at 5-11, that spall would not penetrate more than 350 to 400 feet. However, Dr. Robert Burridge, Associate Professor of Mathematics at New York University, pointed out an error in the AEC's model, and calculated that spall could occur to a depth of 1200 feet. The most recent report on this subject from Lawrence Livermore Laboratory received by TOSCO under a covering letter dated July 10, 1972, appears to acknowledge

that the AEC's earlier computation model was in error with respect to an important assumption - namely that presumption of zero tensile strength in the overlying rock would result in a conservative estimate with respect to depth of spall.

The report also provided additional basic information concerning peak vertical overpressure and attentuation rate. Dr. Burridge believes that if this new basic information is accurate, his earlier estimate of 1200 feet is probably too high. We conclude from our discussions with Dr. Burridge that the earlier AEC estimate of 350 to 400 feet is not demonstrably conservative (and may be much too low) and that additional data on rock properties at any proposed detonation site are needed for improved prediction of spall zone thickness.

The original AEC report by Terhune, the two reports of the TOSCO consultants, and the revised AEC report by Toman are included in Appendices F, G, H, and I, respectively. A comparison of calculation methods for spall and discussions of results is presented in Appendix J. The qualifications of the two principal consultants involved are set forth in Appendix K.

If any of the various estimates of maximum spall depth is correct, it is clear that there will be some spalling of rich oil shale deposits, which in a few places lie less than 200 feet below the surface. A map showing the overburden thickness on top of the Mahogany Marker is reproduced in Figure 10. The Mahogany Marker is located at the top of the very high grade Mahogany Zone. Oil shale of lower grade, but of probable future commercial interest, is present for approximately 50 to 100 feet above the Mahogany Marker.

Estimates have been made, based on Figure 10, of the approximate areas within the Rio Blanco Unit where the Mahogany Marker is within 400, 600, 800 and 1200 feet of the surface:

| Per cent of Area of Unit | Depth of Mahogany Marker |
|---|---|
| 1 | 400 feet or less |
| 5 | 600 feet or less |
| 15 | 800 feet or less |
| 80 | 1200 feet or less |

These estimates indicate that fracturing to a depth of 800 feet would extend into the high grade Mahogany Zone in areas

representing 15 per cent of the Rio Blanco Unit, and the 50 to 100 feet of lower grade oil shale above the Mahogany Zone would be affected over a somewhat larger area.

Shear Failure. The possibility of shear failure, not acknowledged by the AEC, is discussed in detail in the Report of Dr. Burridge. Appendix H, at 12-14. In summary, the conclusion is that the upward-going pressure wave may cause damage to the oil shale by extending existing joints by shearing, especially if the faces are separated by layers of water.

V. THE PROTOTYPE FEDERAL OIL SHALE LEASING PROGRAM, WHICH IS IMPORTANT TO SUBSTANTIAL DEVELOPMENT OF THE PICEANCE BASIN OIL SHALE, AND PROJECT RIO BLANCO ARE IN IRRECONCILABLE CONFLICT.

The President's Energy Message of June 4, 1971, established the importance of the nation's oil shale reserve and its early development. In accordance with this Message, the Department of the Interior announced the Prototype Federal Oil Shale Leasing Program, which includes a series of events leading, in December 1972, to leasing, by competitive bidding, two tracts in each of the states of Colorado, Utah, and Wyoming.

A principal purpose of the leasing program is to establish the environmental acceptability, to the nation and to the States concerned, of further leasing of federal land. Success of the leasing program is vital to large scale development of the oil shale industry because 80 per cent of the reserves of the Piceance Basin, averaging 25 gallons per ton, underlie federal land.

Industry has thus far shown considerable interest in the leasing program. The Department of the Interior reported (news release of November 2, 1971) an aggregate commitment by industry of nearly $2 million in the informational core drilling phase of the program. Ending in January, 1972, industrial participants nominated 13 different tracts in the Piceance Basin, located as shown in Figure 2.

The two tracts selected in the Piceance Basin for competitive bidding in December, 1972, are also shown in Figure 2. This map

also shows the outline of the Rio Blanco Unit that makes evident the conflict between Project Rio Blanco and the leasing program.

The seismic impact of full field development of Project Rio Blanco on development of the federal lease tracts is overwhelming. One of these tracts is totally within the Rio Blanco Unit and the other tract is contiguous with the Unit. Development of these tracts for any purpose--experimental or commercial underground mining and experimental or commercial retorting--would be impossible until the nuclear blasting program is completed.

The threat of development of the Rio Blanco Unit should be expected to have a serious adverse effect on the competitive bidding for the federal lease sites now scheduled for December 1972. Bidders who understand the magnitude of the incompatibility of the Rio Blanco and Leasing Program projects, may stipulate in the bid that money will not be paid until meaningful access to the property is feasible and that the bid can be withdrawn if nuclear blasting, which could damage mineability of the reserves and increase the cost of access, occurs under or near the reserves.

There appears to be no way in which "coordinated planning" called for in the Environmental Statement, at 6-5, can resolve the incompatibility between oil shale development and the nuclear stimulation of Rio Blanco Unit gas deposits. The conflict with the Federal Leasing Program phase of oil shale development is particularly acute.

VI. NO BENEFIT TO THE PLOWSHARE PROGRAM IS DERIVED FROM THE FACT THAT PROJECT RIO BLANCO IS LOCATED IN THE PICEANCE BASIN.

A. The location of the Rio Blanco test project in the Piceance Basin is not technologically necessary to continued progress in techniques of nuclear stimulation.

The sponsors of the Project have not demonstrated or argued that the test location is necessary to orderly progress in development of nuclear gas stimulation technology. Rio Blanco, while perhaps being a "logical"[10/] step in the process is not apparently a necessary one.

The AEC defines the objectives of Rio Blanco as follows (Environmental Statement at p. 2-7):

> The major objective of Project Rio Blanco is to prove that nuclear stimulation using multiple explosives can work in a thick geologic section consisting of several lenticular and noninterconnected gas sands.
>
> Specifically it anticipated that the Rio Blanco experiment will provide information on:
>
> 1. The degree to which stimulation of a thick geologic section is effective.
>
> 2. The degree to which the quality of gas is improved over that obtained from Gasbuggy and Rulison by the use of a low-tritium-producing explosive designed specifically for gas stimulation.
>
> 3. The interactions among vertically-spaced nuclear explosives fired simultaneously.
>
> 4. The economics of multiple nuclear explosions to stimulate gas production enabling better extrapolation to the development of the entire field.

---

10/ Environmental Statement at 2-7.

5. The refinement of predictions of some environmental effects.

The Piceance Basin location is not an essential consideration in developing any of these five items of information except item 4 which is clearly of limited applicability. Thus, Wagon Wheel will involve structures twice as thick as Rio Blanco; no reason appears why the effect of low-tritium-producing devices can not be ascertained at the Gasbuggy, Rulison or Wagon Wheel sites; if the nature of the Piceance Basin rock is controlling, the experience there will be inapplicable to other situations, and if rock is irrelevant, the test could be adequately performed at the AEC's own testing grounds. Item 4 relates exclusively to cost analysis of full development of this particular project; and the only special environmental effects (item 5) to be learned at Rio Blanco appear to be those detrimental to the oil shale resource.

Project Rio Blanco will undoubtedly increase the sum of knowledge about nuclear stimulation, as any nuclear stimulation experiments anywhere would. But the Project as such is not a unique or necessary source of nuclear stimulation information.

B. <u>There are other locations where nuclear stimulation of natural gas has greater potential for success and where development of other resources would not be impaired</u>.

There are areas in the Rocky Mountain Region other than the Piceance Basin, having larger reserves than the Rio Blanco Unit, where development could proceed without endangering any other substantial mineral resource.

The table below notes that the Piceance Basin gas reserves are estimated to be the smallest of the four Rocky Mountain basins. Some oil shale reserves of a lesser extent and a lower grade than the Piceance Basin are present in the Uinta Basin in Utah and the Green River Basin of Wyoming. These oil shale regions are mapped along with the gas regions in Figure 11, and it can be seen that a large portion of these gas bearing regions would be available for nuclear stimulation without the risk of disturbance of the oil shale resource and without delaying the development of the major deposits of oil shale in Colorado.

Estimated increase in reserves of natural gas in four major Rocky Mountain basins, assuming the effective use of nuclear explosives. 11/

| Basin * | Aerial extent with productive potential ($mi^2$) | Assumed productive area ($mi^2$) | Number of known gas-bearing formations | Total sand thickness (ft) | Productive thickness (ft) | Increased recovery using nuclear explosives (Tcf)** |
|---|---|---|---|---|---|---|
| Uinta | 8,900 | 1,800 | 4 | 1,700 | 680 | 61 |
| Piceance | 3,900 | 800 | 4 | 1,200 | 480 | 19 |
| Green River | 19,000 | 4,000 | 7 | 2,500 | 1,000 | 199 |
| San Juan | 10,600 | 2,000 | 3 | 1,100 | 440 | 38 |
| | | | | | | 317 |

*The large Paradox basin is too sparsely developed to permit a reasonable evaluation.
**Tcf= trillion cubic feet

11/ "An Analysis of Nuclear-Explosive Gas Stimulation and the Program Required for its Development", April 20, 1971, prepared for U.S. Atomic Energy Commission under contract No. W-7405-Eng-48, by Lawrence Radiation Laboratory, University of California, Livermore.

## CONCLUSION

For all of the above stated reasons, Project Rio Blanco and the development of the Rio Blanco Unit is not in accordance with the President's Energy Message of June 4, 1971 and should not be carried out. Instead, the objectives sought to be accomplished by this Project should be promptly and diligently pursued at the available alternative sites.

APPENDICES

# THE INCOMPATIBILITY OF NUCLEAR GAS STIMULATION WITH OIL SHALE DEVELOPMENT IN THE PICEANCE CREEK BASIN, COLORADO

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Figure 4. Map of Piceance Creek Basin showing isopach of $\geq 4$ per cent soluble $Al_2O_3$ (Dawsonite)
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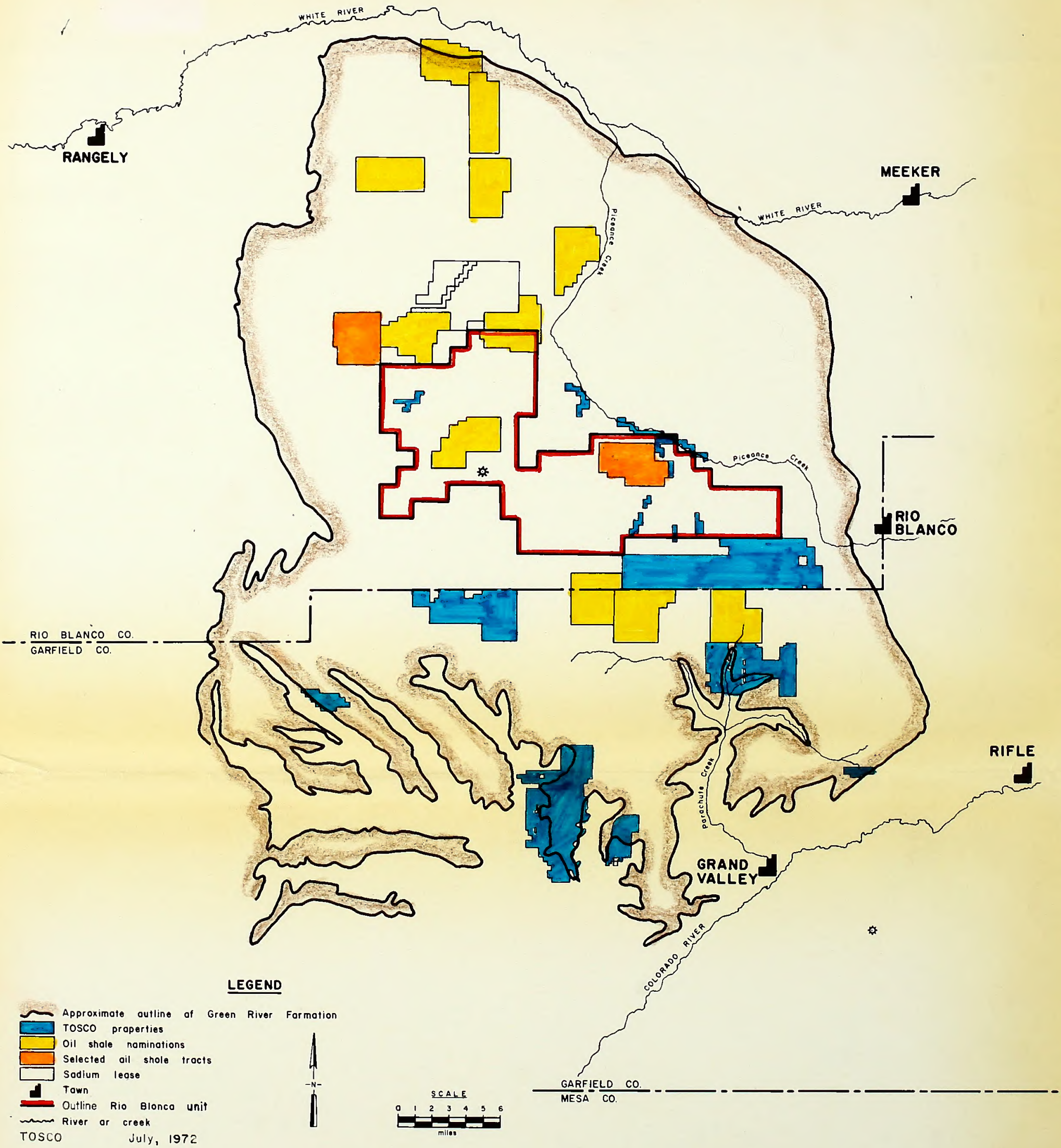
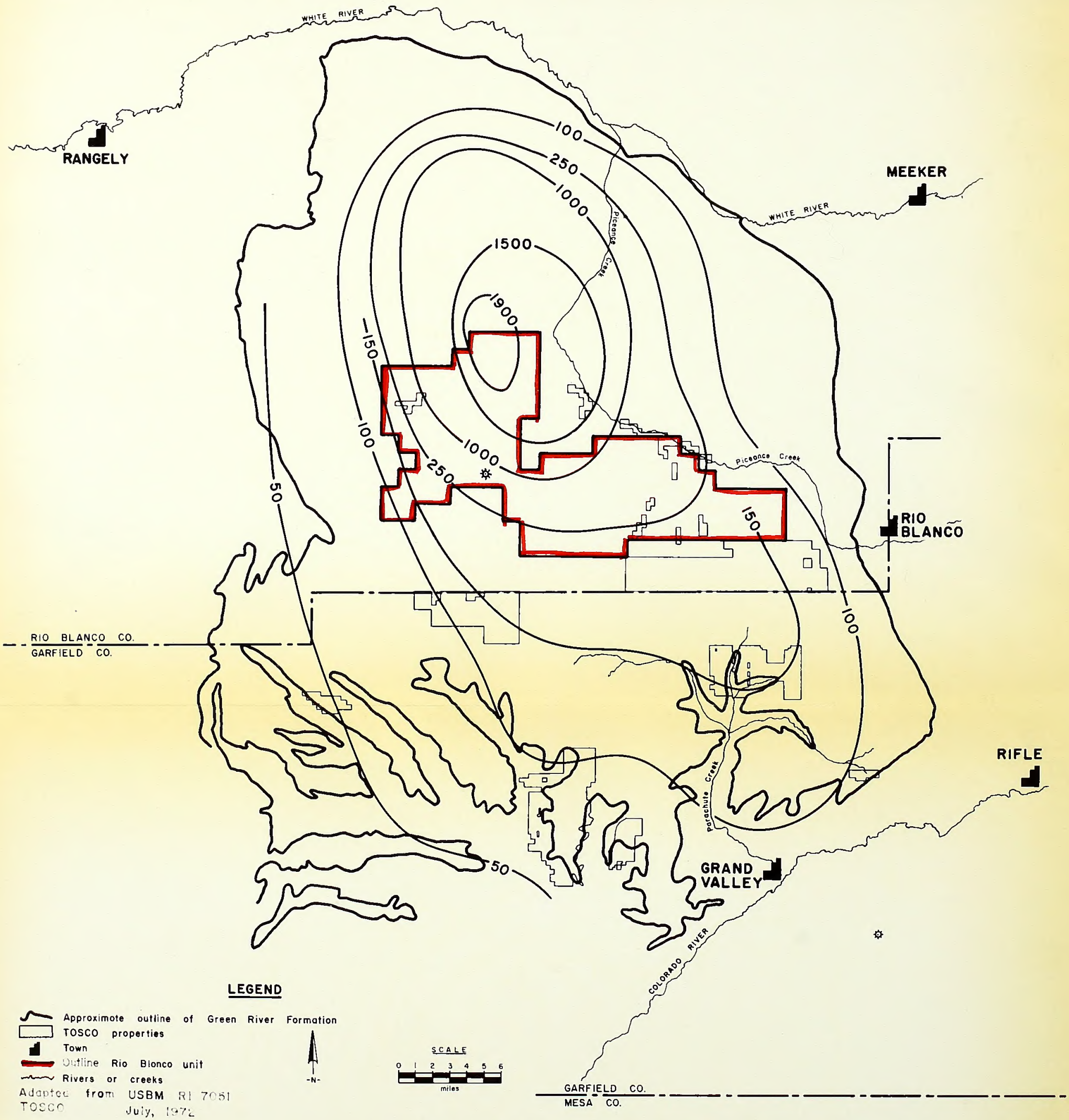
APPENDIX A

Figure No. 1
Picture of Colony Development Operations 1000 ton per day semi-works plant at Parachute Creek, Colorado

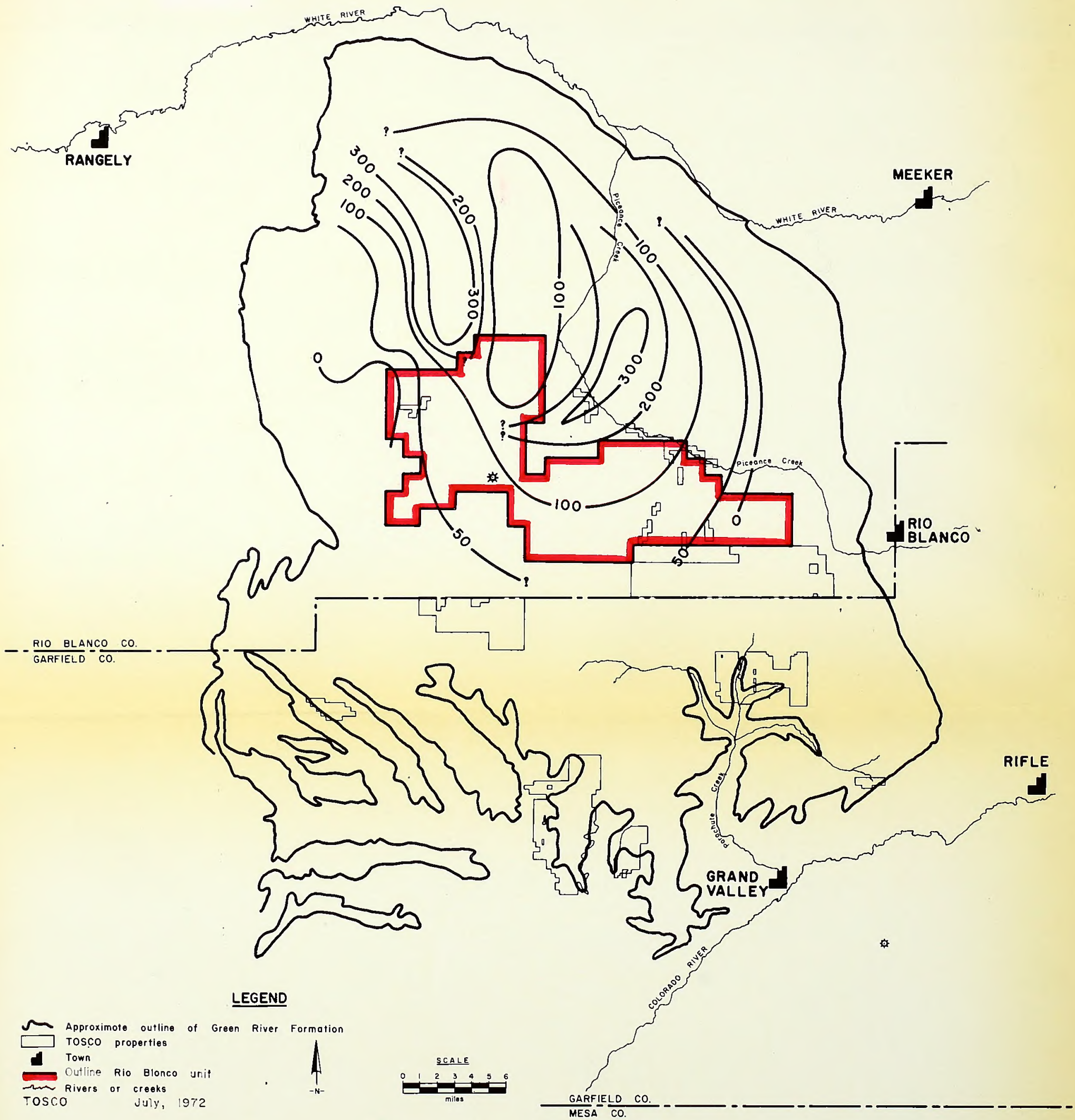



PICEANCE CREEK BASIN, COLORADO

FIGURE 2

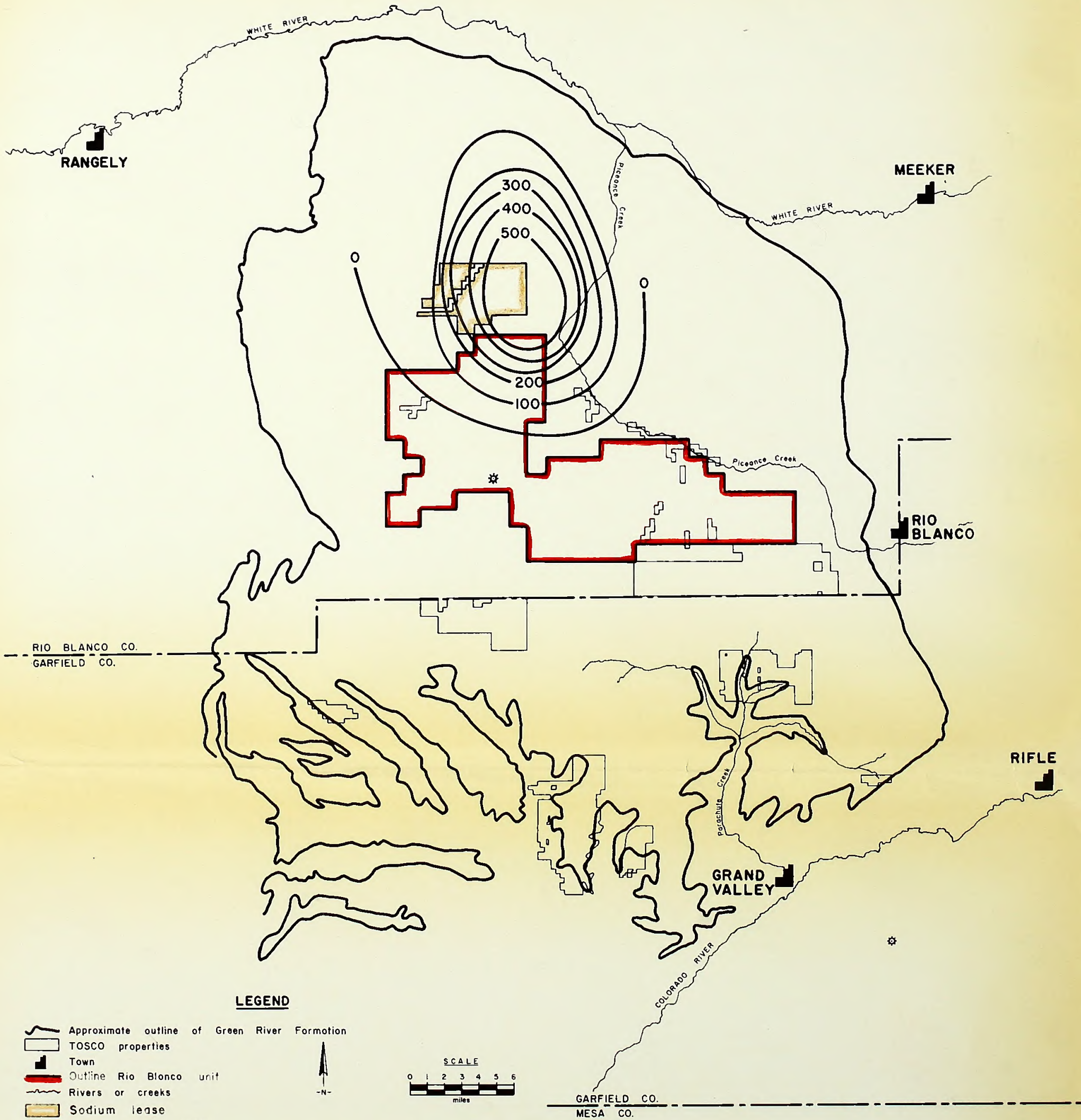



PICEANCE CREEK BASIN, COLORADO
ISOPACH OF 25 GPT OIL SHALE
FIGURE 3




PICEANCE CREEK BASIN, COLORADO
ISOPACH OF ≥ 4% SOLUBLE $Al_2O_3$

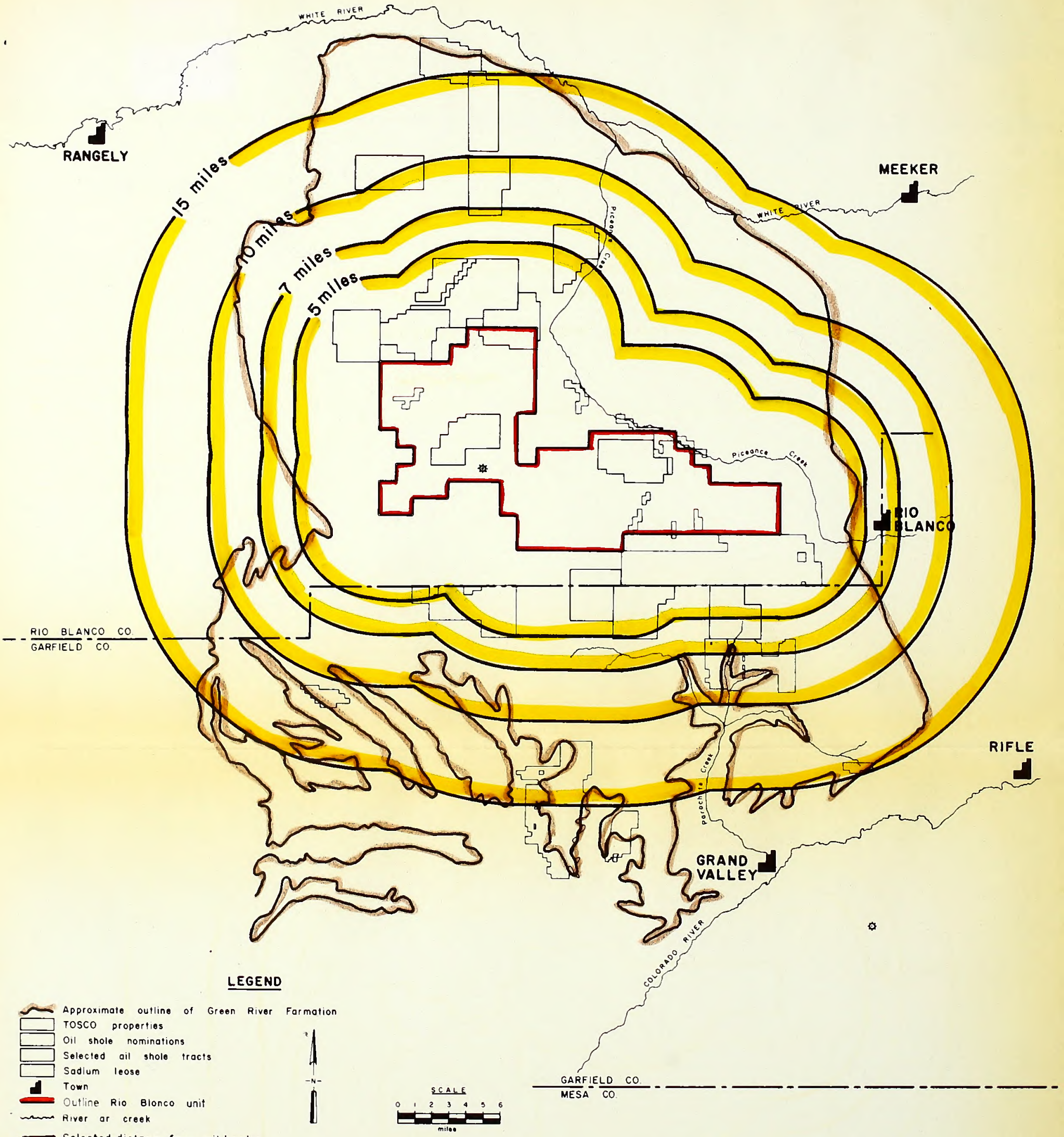
FIGURE 4




PICEANCE CREEK BASIN, COLORADO
ISOPACH OF ≥ 30% NAHCOLITE

FIGURE 5

100
200
300
400
500
REEKEM




RICEANCE CREEK BASIN, COLORADO

RIO BLANCO UNIT AND AREAS INCLUDED
WITHIN SELECTED DISTANCES FROM UNIT BORDER

FIGURE 6

Figure No. 7

Expression of jointing on mine roof surface. Note evidence of leaching and mineral deposition along fracture pattern.

Figure No. 8

Expression of high-angle jointing in mine pillars.

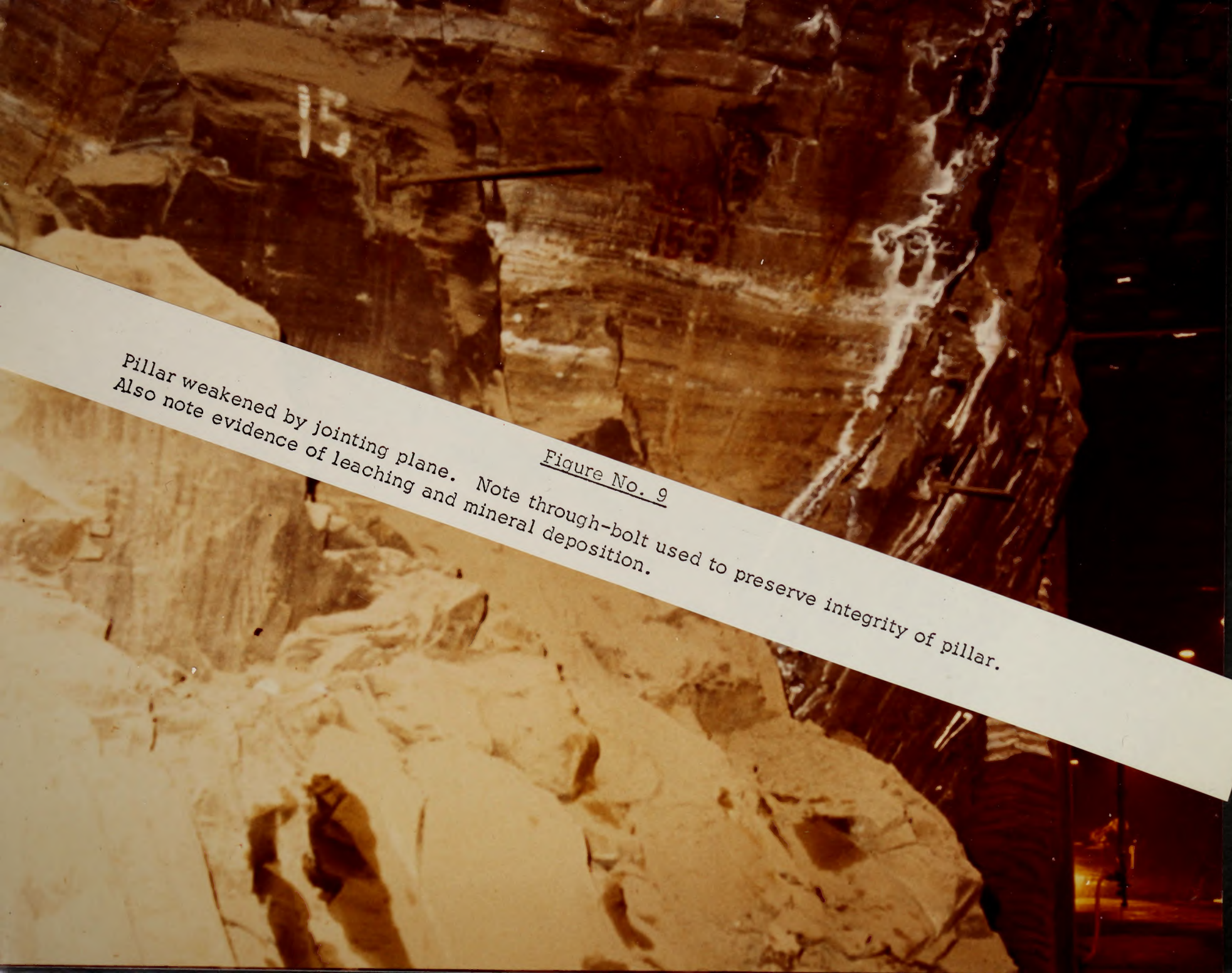



Figure No. 9

Pillar weakened by jointing plane. Note through-bolt used to preserve integrity of pillar. Also note evidence of leaching and mineral deposition.

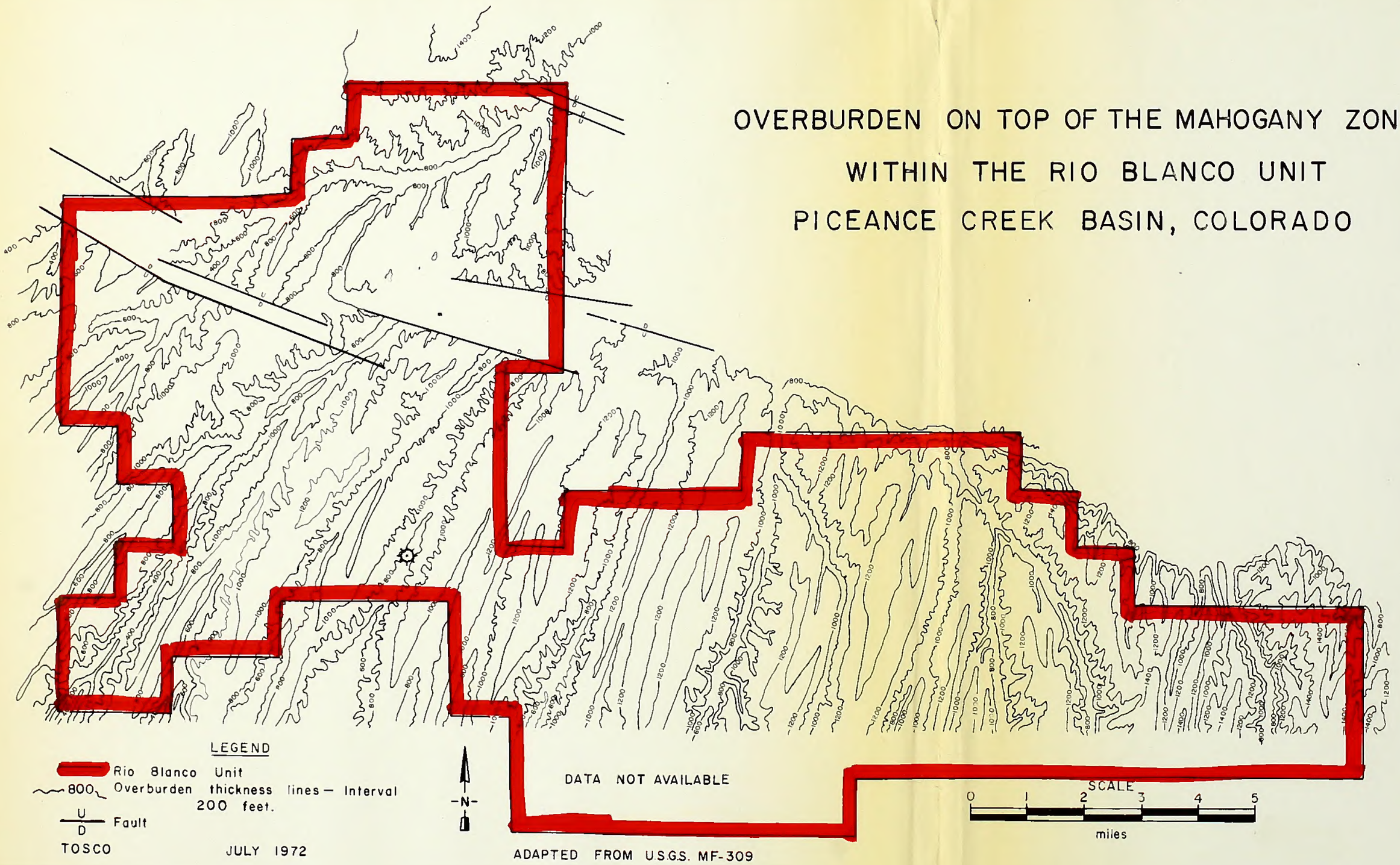
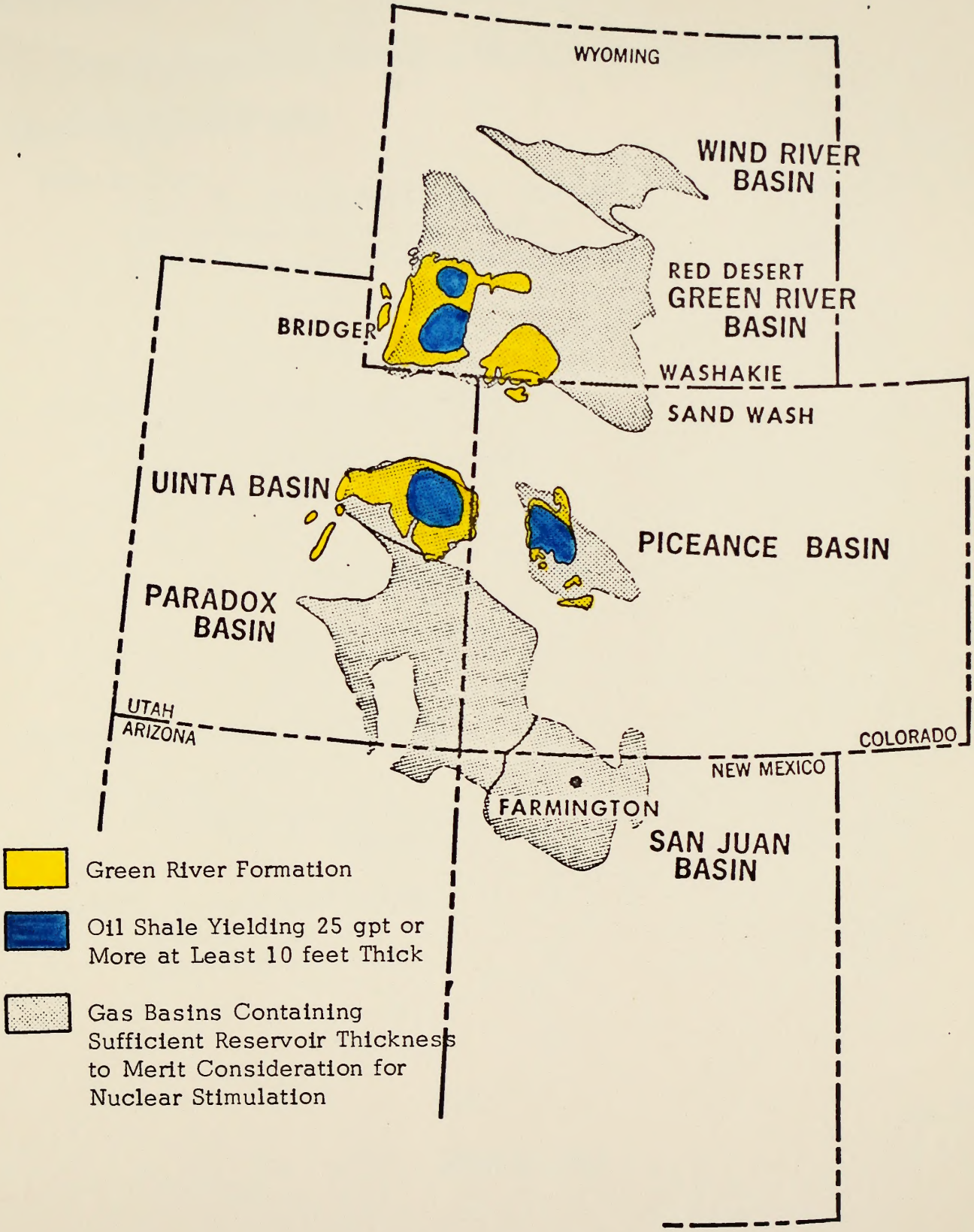

OVERBURDEN ON TOP OF THE MAHOGANY ZONE
WITHIN THE RIO BLANCO UNIT
PICEANCE CREEK BASIN, COLORADO
LEGEND
Rio Blanco Unit
800 Overburden thickness lines — Interval 200 feet.
U D Fault
TOSCO
JULY 1972
N
DATA NOT AVAILABLE
SCALE
0 1 2 3 4 5
miles
ADAPTED FROM U.S.G.S. MF-309

FIGURE 10




OIL SHALE AND GAS BASINS OF THE ROCKY MOUNTAIN STATES

Reference: Project Gasbuggy, A Government-Industry Natural Gas Production Stimulation Experiment Using Nuclear Explosives, NVP-1, September 15, 1967.

FIGURE 11

APPENDIX B

APPENDIX B

## TOSCO AND COLONY INVESTMENT IN OIL SHALE, 1955-72*

### Development Expenditures

| | | |
|---|---|---|
| Joint Venture | | |
| Colony Development Company, 1964-67 | $10,289,000 | |
| The Oil Shale Corporation, 1966-69 | 4,180,000 | |
| Colony Development Operation, 1969-72* | 24,174,000 | |
| Sub Total | $38,643,000 | |
| TOSCO, Outside Joint Venture, 1955-72* | | |
| Direct | $ 9,832,000 | |
| General and Administrative Costs | 12,260,000 | |
| Interest Expense | 3,105,000 | |
| Sub Total | $25,197,000 | |
| TOTAL | | $63,840,000 |

### Reserves Acquisition Expenditures

| | | |
|---|---|---|
| Joint Venture | | |
| Patented Properties & Options to Purchase (Estimate**) | $28,000,000 | |
| TOSCO, Outside Joint Venture | | |
| Patented Properties | 784,000 | |
| Unpatented Properties | 2,700,000 | |
| Sub Total | $ 3,484,000 | |
| TOTAL | | $31,484,00 |
| GRAND TOTAL | | $95,324,00 |

*Expenditures for 1972 include budget projections through December 31, 1972

**TOSCO has invested approximately $5,600,000 in the acquisition of a 20% interest in these properties and options. The figure reported above assumes the basis of the co-venturers to be proportionately the same as TOSCO's.

APPENDIX C

## APPENDIX C

## RESOURCE COMPARISON

| | Rio Blanco Unit | Piceance Creek Basin |
|---|---|---|
| Surface area included | 145 sq. mi. | 1302 sq. mi.[6] |
| **Oil Shale** | | |
| Total reserves estimated in place[4] | 111 billion bbl | 450 billion bbl |
| Total recoverable reserves[3] | 55.5 billion bbl | 225 billion bbl |
| Grade[4] | 25 GPT (avg.) | 25 GPT (avg.) |
| Energy in recoverable reserves[7] | 333,000 trillion Btu | 1,350,000 trillion Btu |
| **Gas** | | |
| Total reserves estimated in place at 60-70 million SCF/sq. mile[1] | 10,150 billion SCF | |
| Total most probable recovery over 20 years[2] | 3,480 billion SCF | |
| Energy in recoverable reserves[8] | 3,480 trillion Btu | |

(1) Economics of Nuclear Stimulation, CER Geonuclear Corporation, Las Vegas, Nevada, October 29, 1970, page 3.

(2) As predicted by CER, "Although recoveries beyond a 20-year period would be expected, the present value of such recoveries is negligible, and hence such recoveries have been excluded from the single well financial analysis." Economics of Nuclear Stimulation, CER Geonuclear Corporation, Las Vegas, Nevada, October 29, 1970, page 3.

(3) Assumes 50 percent recovery. The Colony Development Operation presently extracts 65 to 70 percent of the mining horizon. As yet no techniques have been demonstrated for similar recoveries in the thick zones, although it is anticipated that techniques can be developed which will recover at least 50 percent and perhaps as much as 70 percent.

(4) Bureau of Mines Report of Investigations 7071, January 1968, Figure 7, Isopachous Map of 25 GPT Oil Shale, Piceance Creek Basin, Colorado.

(5) Figure of 111 billion bbl. for Rio Blanco Unit is ±10 percent. Figure of 450 billion bbl. for Piceance Basin is taken from D. C. Duncan and V. C. Swanson, Organic Rich Shale of the United States and World Land Areas, Geological Survey Circular 523, Wash., D. C. (1965).

(6) Area of Piceance Basin estimated from Outline of Basin shown on Figure 2.

(7) One barrel of crude shale oil has an energy content of 6 million Btu.

(8) One SCF of gas has an energy content of 1000 Btu.

APPENDIX D

APPENDIX D

DAMES & MOORE

CONSULTING ENGINEERS IN THE APPLIED EARTH SCIENCES

SUITE 100, 10597 WEST 6TH AVENUE · DENVER, COLORADO 80215 · (303) 232-6262
TWX: 910-931-2600

July 18, 1972

The Oil Shale Corporation
1700 Broadway
Denver, Colorado 80202

Attention: Mr. Louis H. Yardumian, Jr.
Vice President

Gentlemen:

RE: Seismic Effect of Rio Blanco on Proposed Colony Facilities

1) At your request, we, in association with the Ralph M. Parsons Company of Los Angeles, California, have addressed the potential seismic effects of the proposed Rio Blanco gas stimulation project on proposed Colony structures.

2) At the present time, Parsons has a proposed oil shale processing facility under design for Colony. The facility is being designed in conformance with conventional practice (applicable portions of the Uniform Building Code, including seismic provisions for Zone 1).

3) Parsons has examined the additional cost of constructing these facilities to safely respond to the ground motions predicted in the environmental statement issued by the AEC for the Rio Blanco project (Wash-1519, April 1972), assuming these motions would apply to full field development.

4) We have utilized the peak resultant vector acceleration, velocity, and displacement ground motion predictions from the environmental statement (Figures 3-1, 3-2, and 3-3) to develop predicted peak structural motions in the processing facility. The level of ground motion selected for examination is equal to a mean +1 sigma value of 0.9g for the peak resultant vector acceleration and the mean +1 sigma values for velocity and displacement ground motion. This level of ground motion corresponds to a slant distance of 7 miles (11 km), which represents the closest approach of blasts during full field development. Since the figures presented are in terms of vector resultant motion, they have been resolved into single components of motion by multiplying by 0.707.

5) The mean +1 sigma predicted values were used in the analysis because data are presented in the impact statement for motion at this prediction level. The use of this level should not be considered as a

recommendation that the level should be used for a commercial design. In view of the high cost of these facilities and the risk of fire in case of damage, the level selected must provide a high confidence of safety.

6) Structural response spectra were prepared following current AEC practice from the peak predicted ground motions at the site for the selected level of ground motion (mean +1 sigma at 7 miles). Five key structural units in the refinery have been analyzed by the Parsons Company using these predicted structural response spectra. These structures were originally designed to respond elastically to UBC Zone 1 earthquake or wind, which ever might control, with an appropriate safety factor to yield. Using the predicted structural motions from the Rio Blanco shots, the structures were redesigned to remain elastic under the much larger blast motion; however, all safety factors were eliminated and the structures were allowed to just reach yield levels. The cost of the redesigned structural units are compared with the original design costs in the following table.

TABLE OF CONSTRUCTION COSTS
AS A FUNCTION OF GROUND MOTION ENVIRONMENT

| Structural Unit | Original UBC | Rio Blanco Shot +1 Sigma | Percentage Change in Cost |
|---|---|---|---|
| Fractionator vessel foundation | $60,549 | $131,210 | 117% |
| Typical pipe support and footing | 4,705 | 5,515 | 17.2% |
| Conveyor system support truss | No change | No change | No change |
| Centrifuge building | 64,000 | 88,000 | 37.5% |
| Decoking water tank | 22,000 | 44,000 | 100% |

7) It is difficult to extrapolate the predicted behavior of the above units, and their costs to costs for the complete facility, since only simple structures were analyzed due to the limited time available. However, it is apparent that the incremental costs for construction of the complete facility to withstand these high seismic forces could be sizeable.

8) The Ralph M. Parsons Company has had extensive experience in the design of major industrial facilities for dynamic forces from nuclear blasts and earthquake motions. They have engineered and constructed nuclear power plants and major anti-missile installations to mention a few of their more recent project areas involving sophisticated application of structural dynamics. We consider their estimate and calculations valid.

Very truly yours,

DAMES & MOORE

David J. Leeds

David J. Leeds
Senior Seismologist

Larry K. Davidson

Larry K. Davidson
Registered Prof. Engineer
State of Colorado
No. 8890

DJL/LKD/dls

APPENDIX E

## APPENDIX E

# EFFECT OF INCREASING FREQUENCY OR DECREASING STRENGTH OF FRACTURES UPON MINEABILITY USING THE ROOM AND PILLAR METHOD

By: Robert K. Murray, Manager
Mining Department
The Oil Shale Corporation

Rock stability problems are cause for concern during mining or construction operations because rock failures within mining excavations have caused significant injury and loss of life. Rock failures in mine excavations may be categorized into roof and pillar failures. Roof failures are of the most concern since they usually occur suddenly with little advance warning. While pillar failures can occur violently and suddenly, they usually are much slower in developing and give adequate warning prior to final, complete failure. There are different failure mechanisms in various rock types; this discussion will be limited to rock structural problems encountered in sedimentary rock masses.

There are essentially three categories of roof failures. The first of these is a simple "gravity fall" caused by a rock slab falling because the rock is not sufficiently strong to support itself across a given opening. This type of fall generally occurs because the rock tensile strength was exceeded. A second type of roof failure is a shearing type failure that can result for two reasons.

(1) If a rock mass is subjected to high tectonic horizontal force, placing the roof rock into a compressive condition, shear failures can result. (2) Shear failures which occur less frequently than (1) above can also result from high gravity loadings of an immediate roof slab. The third type roof failure that can occur is a simple "punching" of the pillar into the roof or floor material. This can occur when the pillar rock is significantly stronger than either the roof or floor material.

Pillar failures may also be classified into three broad categories. The rock on the exterior of pillars may fail violently by spalling. High shearing stresses build up when a pillar becomes loaded from the weight of the overburden. A sudden release of this strain energy can cause individual, large pieces of rock to be projected from the intact rock mass. The exterior of pillars can also slab off less violently as a series of vertical plates, again due to shear failure from the pillar taking load from the overburden. A third major category is a complete collapse of a single pillar or a series of pillars due to inability to withstand loading from the overburden. This type of failure can manifest itself in two ways. If the rock is highly jointed, the failure can occur by movement along joint planes which are under shear stress. If the rock mass is not jointed the failure will occur as an actual shear failure of the rock material.

As has been indicated, shear strength of rock masses is an important parameter of rock structural failures. Shear strength of intact (unfractured) rock masses is obviously greater than shear strengths of fractured rocks. In order for an intact rock mass to fail in shear, the actual particles of rock material must be made to slide apart from one another. A shear failure of a fractured rock mass does not require the "tearing" of rock material. Such failure simply requires the sliding of one mass against another after frictional resistance is overcome. The important point is that increased fracture frequency or disturbance along existing fractures (which tends to decrease the frictional resistance) decreases the competency of a rock mass because these adverse occurrences decrease the ability of a rock mass to resist shearing stresses.

As the foregoing indicates, fracture characteristics have an important effect on mineability. It is generally accepted among mining engineers and specialists in rock mechanics that an increase in the number of fractures in rock, or a decrease in the strength of existing fractures, tends to reduce the overall structural quality of the rock. One would expect that room and pillar mining in a lower quality rock would entail some or all of the following disadvantages among others: use of smaller, less efficient equipment

due to restrictions on feasible room size, necessity for increased use of rock bolting, timber or steel support, Guniting, Shotcreting, or poured reinforced concrete support.

At least two methods for estimating rock quality resulting from fracture frequency are in common use. Where large surfaces can be examined, such as in an open mine, one may simply measure the spacing of the fractures. We have made such determinations in the Colony oil shale mine at Parachute Creek, and although we have found no quantitative relationship, the areas of higher joint frequency have definitely exhibited the most instability.

An indirect method for determining rock structural competency is the Rock Quality Designation (RQD) system devised by Donald U. Deere, until recently a professor of civil engineering at the University of Illinois. Commonly rock mechanics information is obtained from test core borings. Very frequently the lower the core recovery and the more fractured the core, the more incompetent the rock is found to be. The RQD concept was developed to work with retrieved core borings.

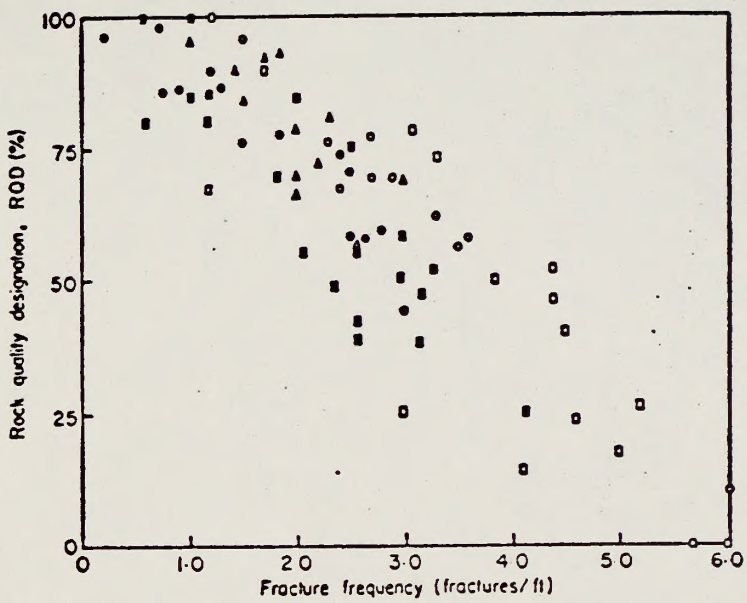
Very simply, RQD is the percentage of recovery of competent core. Competent core is arbitrarily determined as any individual core piece that exceeds 4 inches in length. However, two or more pieces of core broken by coring, as evidenced by fresh fracturing,

are included as competent core so long as the combined length of such pieces exceeds 4 inches. RQD is expressed as a simple percentage.

Deere has arbitrarily assigned descriptive rock qualities to the following rock quality designations:

| RQD % | Description of Rock Quality |
|---|---|
| 0 - 25% | Very Poor |
| 25 - 50% | Poor |
| 50 - 75% | Fair |
| 75 - 90% | Good |
| 90 - 100% | Excellent |

Although the system was devised for use with dam foundations and tunnels and for igneous rocks, Deere reports that it has been applied successfully with sedimentary rocks as well. At least one small sampling of data indicates that the expected correlation between rock quality designation and fracture frequency does exist. The following plot of data indicates this relationship.




Climax stock
- ○ Tunnel wall, across joints
- △ Tunnel wall, parallel to joints
- □ NX core

NX core
- ● Dworshak Dam, granite gneiss
- ▲ John Day Basalt
- ■ Hackensack Siltstone

**Figure 1.9** Correlation of rock mass quality indices : fracture frequency and RQD *

It is apparent that extension of the length of existing fractures has the same effect as creating a new fracture in the region of the extension. It is also apparent, particularly in the context of determining RQD's, that breaking the weak bonds of existing but "recemented" fractures also lowers the rock quality.

Since the RQD system results in numerical values, it is tempting to try to translate RQD variations into mine design changes or mining cost predictions. However, the author is not aware that anyone has learned to do this on a quantitative basis. Because

---

* Stagg, E. G. and O. C. Zienkiewicz, Rock Mechanics in Engineering Practice, John Wiley & Sons, London (1968).

of the nature of the engineering properties of rock, rock mechanics is not an exact science as is structural design with steel or other homogeneous, elastic, and isotropic engineering materials.

In addition to fracture frequency, there are many other important variables such as the angles of the fractures and their locations within the mine, the extent of fracture "healing", the frequency of parting planes, and the extent of parting plane consolidation. These are all structural imperfections and are important variables aside from actual intact rock physical properties. Furthermore, actual RQD's determined by field measurements vary over a wide range within a given mining location, so it is often difficult to know whether a modest difference is significant.

Nevertheless, fracture frequency is important, and mining engineers do apply RQD or similar data on an intuitive basis. Each practitioner biases design results on the basis of RQD or fracture frequency according to personal past experience and individual judgment.

APPENDIX F

APPENDIX F

This is an informal report intended primarily for internal or limited external distribution. (The opinions and conclusions stated are those of the author and may or may not be those of the laboratory.) This report is not to be given additional external distribution or cited in external documents without the consent of the author or LRL Technical Information Department.

UCID - 15922

Lawrence Radiation Laboratory

UNIVERSITY OF CALIFORNIA

LIVERMORE

94550

# PREDICTION OF SPALL PHENOMENA AND NEAR SURFACE EFFECTS FOR PROJECT RIO BLANCO

R. W. Terhune

October 18, 1971

Prepared for U.S. Atomic Energy Commission under contract No. W-7405-Eng-48

# PREDICTION OF SPALL PHENOMENA AND NEAR SURFACE EFFECTS FOR PROJECT RIO BLANCO


## ABSTRACT

Project Rio Blanco is a proposed multiple nuclear explosive gas stimulation experiment. The gas sands to be stimulated are overlain by a rich oil shale section. This paper presents a computer study to determine if the oil shale will be fractured by the Rio Blanco experiment.

The calculations used the material properties measured for the Green River oil shale, logging data from two nearby wells, and also material properties developed for Wagon Wheel shale.

The calculations predicted that compressive fracture would not extend beyond 5 cavity radii (350 ft) from the detonation point and that tensile fracture is confined to within 170 ft of the free surface. The peak spall velocity at the surface directly above the detonation point was predicted to be 2.5 m/sec. A series of calculations, using zero tensile strength and the failure surface for a highly fractured shale were made in which layers of various impedance mismatch were examined. Fracture or separation on previous existing fractures was not predicted even though a sharp discontinuous impedance mismatch up to twice those observed was examined.


## INTRODUCTION

Project Rio Blanco is a multiple nuclear explosive gas stimulation experiment. Three 30-kt explosives will be placed in a single wellbore, spaced about 420 ft apart, and detonated simultaneously. The top explosive will be emplaced at a depth of about 6000 ft. In this area of the Piceance Basin, the gas sands are overlain by a rich oil shale section lying between the 400- and 2900-ft depth.

The purpose of this study is to determine if the shock wave expected from the detonation of the Rio Blanco explosives will fracture the Green River formation which contains the oil shale.

## PHENOMENOLOGY OF A NUCLEAR EXPLOSION

Detonation of a deeply buried nuclear explosive creates tens of megabars of stress discontinuity which propagates into the surrounding media. This stress discontinuity (shock wave) departs its energy into the rock and thus attenuates as it propagates radially from the source.

Initially enough energy is released in the region immediately surrounding the explosive to vaporize the rock. Approximately 70 tons of rock are vaporized per

kiloton of explosive energy; additional energy is deposited from the outgoing shock wave to melt the rock up to about twice the radius of vaporization. Beyond this, the rock is fractured until, at large distances from the source, the shock wave has decayed to a point where it propagates elastically. The cavity (formed by the vaporized region) expands until the pressure in the cavity is in equilibrium with the stresses in the rock. This equilibrium point is defined as the cavity radius $R_c$. Tensile and compressive waves are reflected when the shock wave interacts with the ground surface or other interfaces where there is a change in the material properties. Such a subsurface interface may be manifested as a consequence of variations in the material properties between various grades of oil shale (or other geologic layering) that exist 400 to 3000 ft beneath the ground surface. Fracturing will occur if the reflected stress is greater than the tensile strength of the rock layer into which the reflection takes place or if the shear strength of the rock is exceeded by the shear stress in the stress wave. The reflection of the shock wave at the free surface causes layers of the medium to separate and move with the velocity characteristic of the energy that has been trapped in these layers. This phenomenon is referred to as "spall."

## METHOD OF ANALYSIS

Computer programs developed by Cherry and Petersen[1] in conjunction with a compatible determination of material properties developed by Stephens, Schock, and Heard[2-4] have led to a reliable predictive capability for phenomena associated with shock wave propagation. Phenomena such as peak shock stress, particle velocity, extent of fracturing, and spalling have been predicted for numerous underground[1] and cratering[5] experiments. The computer program selected for this analysis is the one-dimensional version named SOC.

The actual design contemplated for Rio Blanco presents a two-dimensional problem. A simplifying assumption required for a one-dimensional analysis is to assume the full yield of Rio Blanco at a point source. For the region above the detonation point this is a conservative assumption, since the top cavity will shield the rock toward the surface from the other two detonations.

## GEOLOGY DESCRIPTION

The detonation points are planned below 5500 ft in the Fort Union formation, which consists of bedded layers of sandstone and shale. Between the depths of 2900 and 5500 ft is the Watsach formation consisting primarily of a dense shale. Between the depths of 400 and 2900 ft is the oil shale. This region is highly bedded with considerable variation in material properties between layers depending upon the grade of the oil shale. Between depths of 800 and 900 ft is an oil rich impermeable region called the Mahogany Zone which separates two aquifer subsystems.

## MATERIAL PROPERTIES

A basic input requirement for the computer models is a description of the material properties. These material properties must include density, sonic velocity, hydrostatic compressibility, and failure envelope. The material properties for the Watsach and the Fort Union formation have not been determined, but they are expected to be similar to the shales from both the Rulison and Wagon Wheel sites.[6-9] The material properties for the Wagon Wheel site have been measured in fairly complete detail. The material properties parameters used for this rock were: density, 2.45 g/cm$^3$; sound velocity, 4 km/sec; and a Poisson's ratio of 0.2. Fortunately, a number of material property measurements have been made on oil shale.[2,1] As mentioned previously, there are considerable differences in the material properties of the oil shale depending upon the amount of oil the shale contains.

Figure 1 illustrates the variation in the material properties with the grade of the oil shale. It can be seen that the density can vary between 1.6 g/cm$^3$ and 2.6 g/cm$^3$. Sonic log travel time ranges from 160 $\mu$sec/ft to 60 $\mu$sec/ft where 160 $\mu$sec/ft corresponds to a compressional velocity of 6250 ft/sec or 1.9 km/sec. A sonic log trave time of 60 $\mu$sec/ft corresponds to a velocity of 16600 ft/sec or 5 km/sec. Figure 2 shows the shear strength of the shale as a function of the mean pressure. The solid lines represent the failure envelope through the unfractured shale. The dashed line is the failure envelope for highly fractured shale. As the amount of oil in the shale increases, the shale becomes ductile at lower pressures. Note that all three curves have a common unconfined compressive strength near the origin.

## THE CALCULATIONAL MODEL

As previously discussed, the site at Rio Blanco has a region from the surface to approximately 3000 ft in depth that is highly layered and variable in its properties. From 3000 ft to the planned detonation point at approximately 6000 ft, the shale is fairly homogeneous. Figure 3 shows a plot of the compressional velocity in feet per second and the density in grams per centimeter cubed for the first 2800 ft from two holes near the Rio Blanco site area. The compressional velocities are from the Fawn Creek No. 3 Well approximately 2-1/2 mi from ground zero. The density logs are from Ryan No. 2 approximately 7 mi from surface ground zero. A consistent feature of the two logs is the discontinuity in both compressional velocity and density at a depth of about 1800 ft. This is consistent with the reflective layer that was determined from the seismic survey conducted in Rio Blanco County.[10] Boardman[11] calculated the impedances (that is velocity times density) for the oil shale at depths between 400 and 2300 ft at the Fawn Creek No. 1 well. The impedances were determined by converting the grades of oil every 10 ft into a density and compressional velocity as shown on Fig. 1. Boardman found the maximum ratio of impedance discontinuities was approximately 1.7 in this interval.

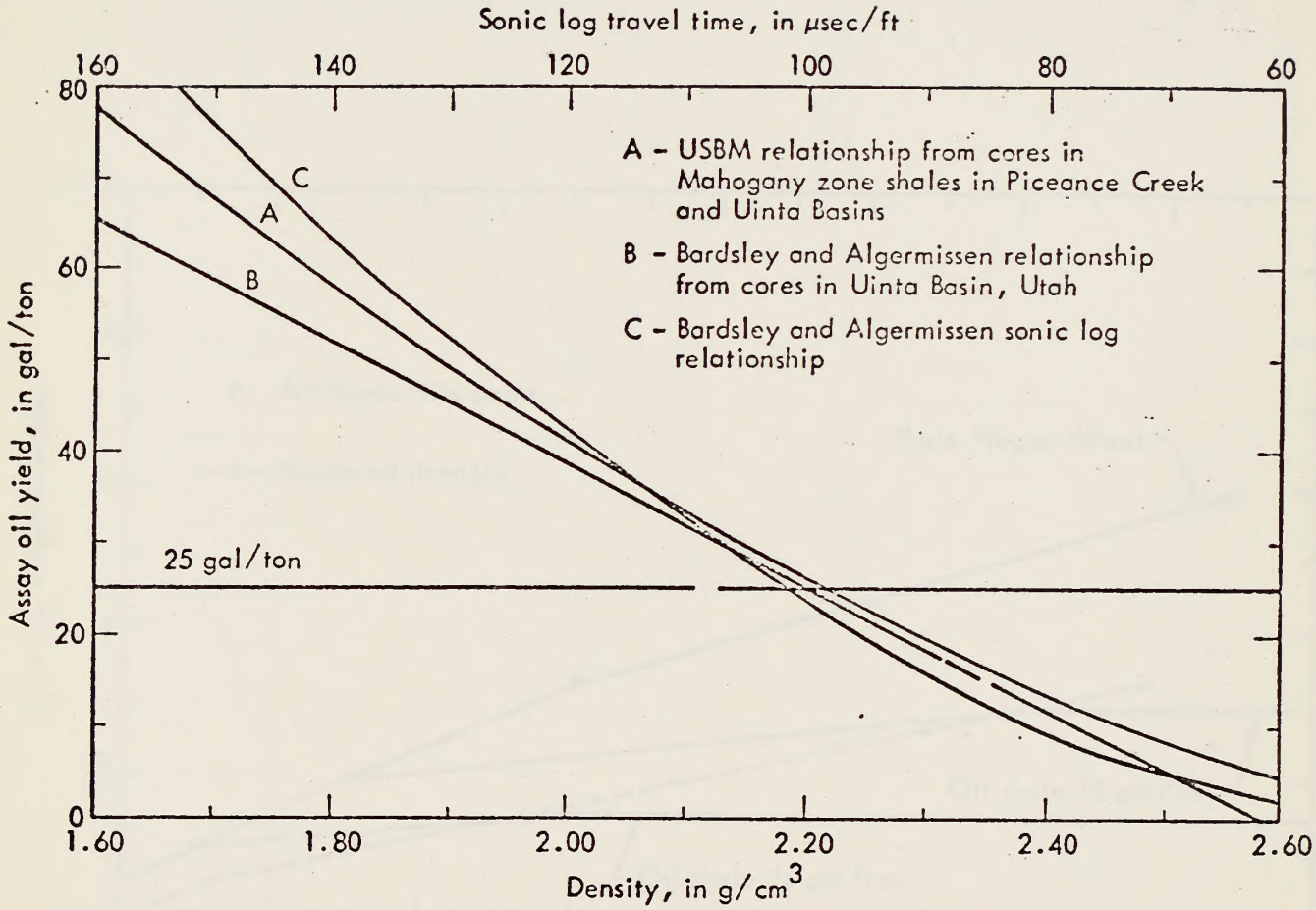



Fig. 1. Relationships between density, velocity, and oil assay established by various investigators.

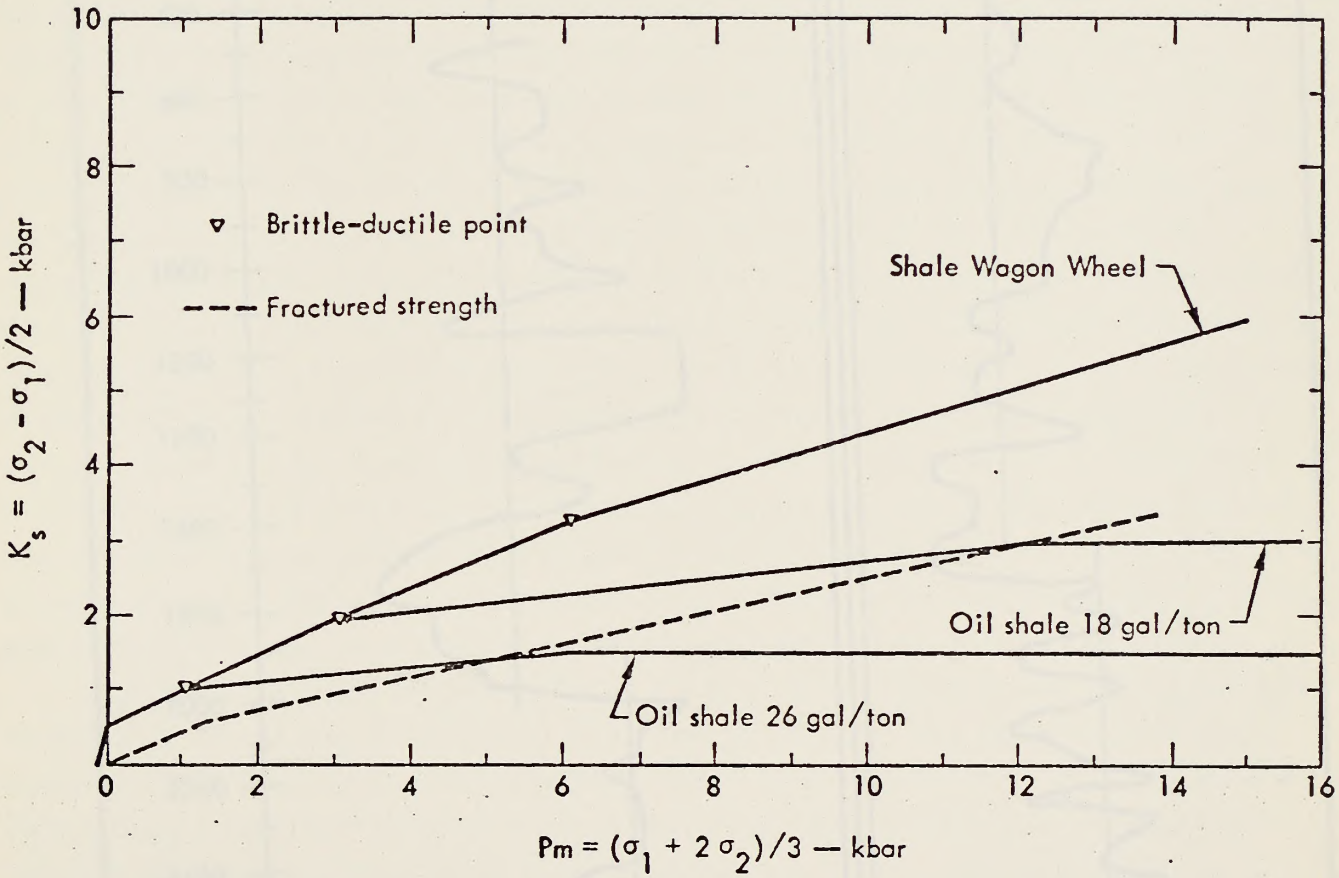



Fig. 2. Shear strength of shale as a function of pressure.

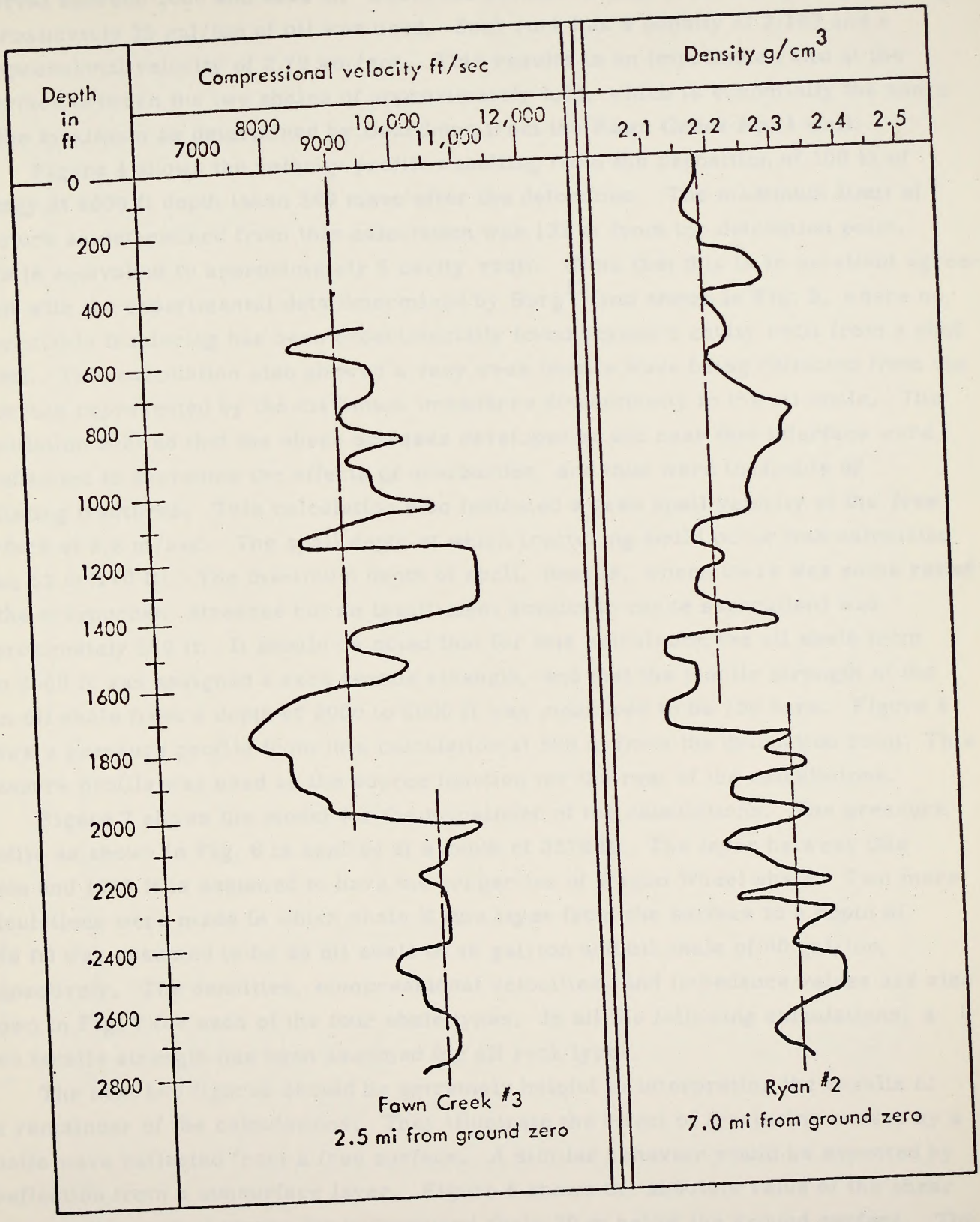



Fig. 3. In situ density and velocity data.

The first calculation used the homogeneous Wagon Wheel shale in the depth interval between 2000 and 6000 ft. From the surface to 2000 ft an oil shale containing approximately 25 gal/ton of oil was used. Such rock has a density of 2.193 and a compressional velocity of 2.79 km/sec. This results in an impedance ratio at the interface between the two shales of approximately 1.65, which is essentially the same as the maximum as determined by Boardman from the Fawn Creek No. 1 well.

Figure 4 shows the velocity profile resulting from the deposition of 100 kt of energy at 6000 ft depth taken 560 msec after the detonation. The maximum limit of fracture as determined from this calculation was 132 m from the detonation point. This is equivalent to approximately 5 cavity radii. (Note that this is in excellent agreement with the experimental data determined by Borg[12] and shown in Fig. 5, where no appreciable fracturing has been experimentally found beyond 5 cavity radii from a shot point). This calculation also showed a very weak tensile wave being reflected from the interface represented by the maximum impedance discontinuity in the oil shale. The calculation showed that the shear stresses developed at and near this interface were insufficient to overcome the effects of overburden, and thus were incapable of initiating fractures. This calculation also indicated a peak spall velocity at the free surface of 2.5 m/sec. The spall depth at which fracturing could occur was calculated to be 52 m (170 ft). The maximum depth of spall, (that is, where there was some relief of the overburden stresses but an insufficient amount to cause separation) was approximately 360 ft. It should be noted that for this calculation the oil shale from 0 to 2000 ft was assigned a zero tensile strength, and that the tensile strength of the lean oil shale from a depth of 2000 to 6000 ft was measured to be 100 bars. Figure 6 shows a pressure profile from this calculation at 800 m from the detonation point. This pressure profile was used as the source function for the rest of the calculations.

Figure 7 shows the model for the remainder of the calculations. The pressure profile as shown in Fig. 6 is applied at a depth of 3378 ft. The layer between this depth and 1966 ft is assumed to have the properties of Wagon Wheel shale. Two more calculations were made in which shale B (the layer from the surface to a depth of 1966 ft) was assumed to be an oil shale of 40 gal/ton and oil shale of 60 gal/ton, respectively. The densities, compressional velocities, and impedance values are also shown in Fig. 7 for each of the four shale types. In all the following calculations, a zero tensile strength has been assumed for all rock types.

The next two figures should be extremely helpful in interpreting the results of the remainder of the calculations. They illustrate the effect of fracturing caused by a tensile wave reflected from a free surface. A similar behavior would be expected by a reflection from a subsurface layer. Figure 8 shows the absolute value of the shear stress vs the normal stress for unfractured shale 30 m below the ground surface. The shear stress strength is shown by the dashed line. Initially, the zone is at point A where the shear stress is zero and confining pressure due to overburden is present. As the stress wave approaches, the shear stress and the normal stress both increase to point B. As the stress wave passes, the shear stress and the normal stress both relax

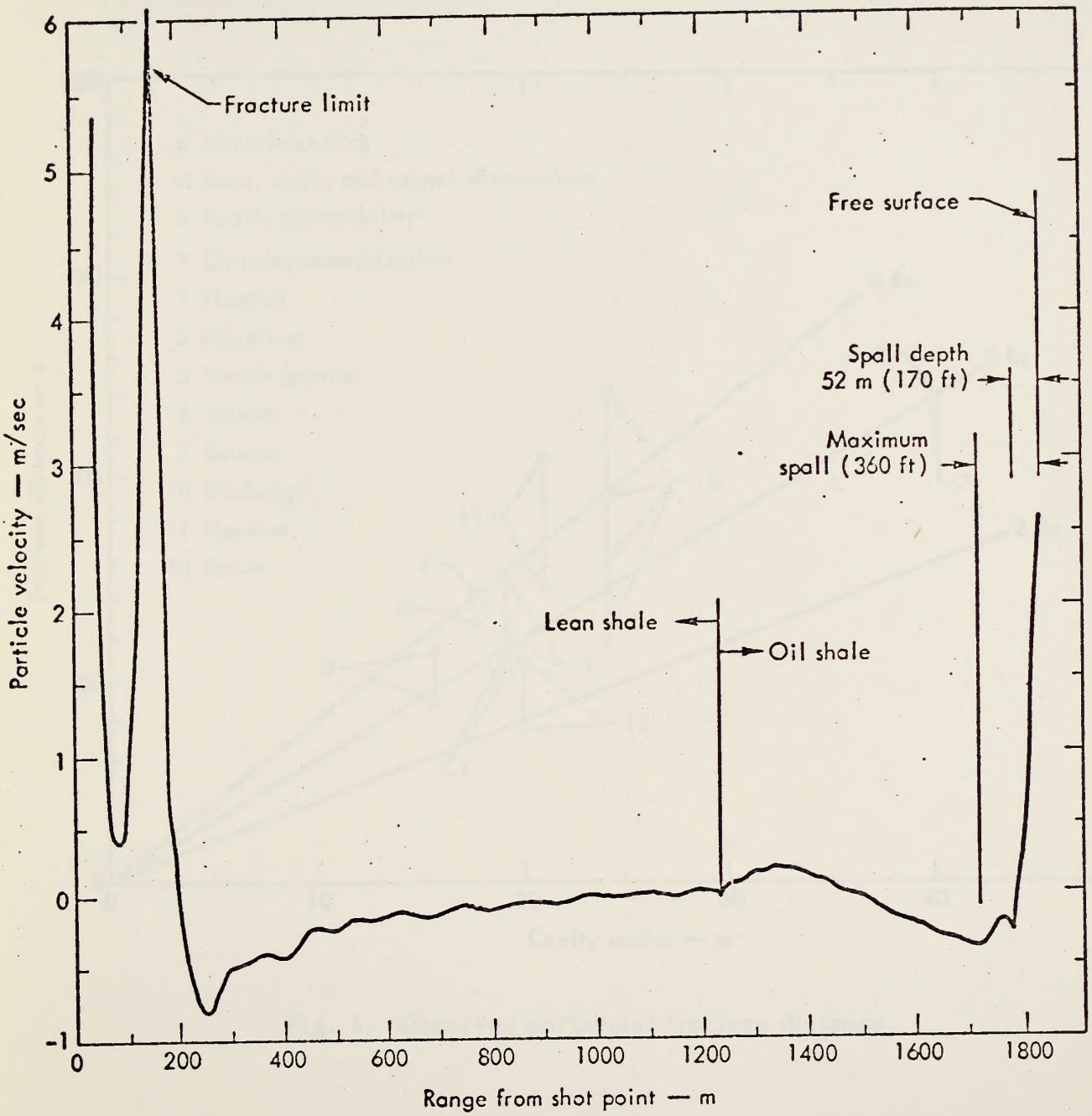



Fig. 4. Velocity profile for 100 kt at 6000 ft depth at time 560 msec.

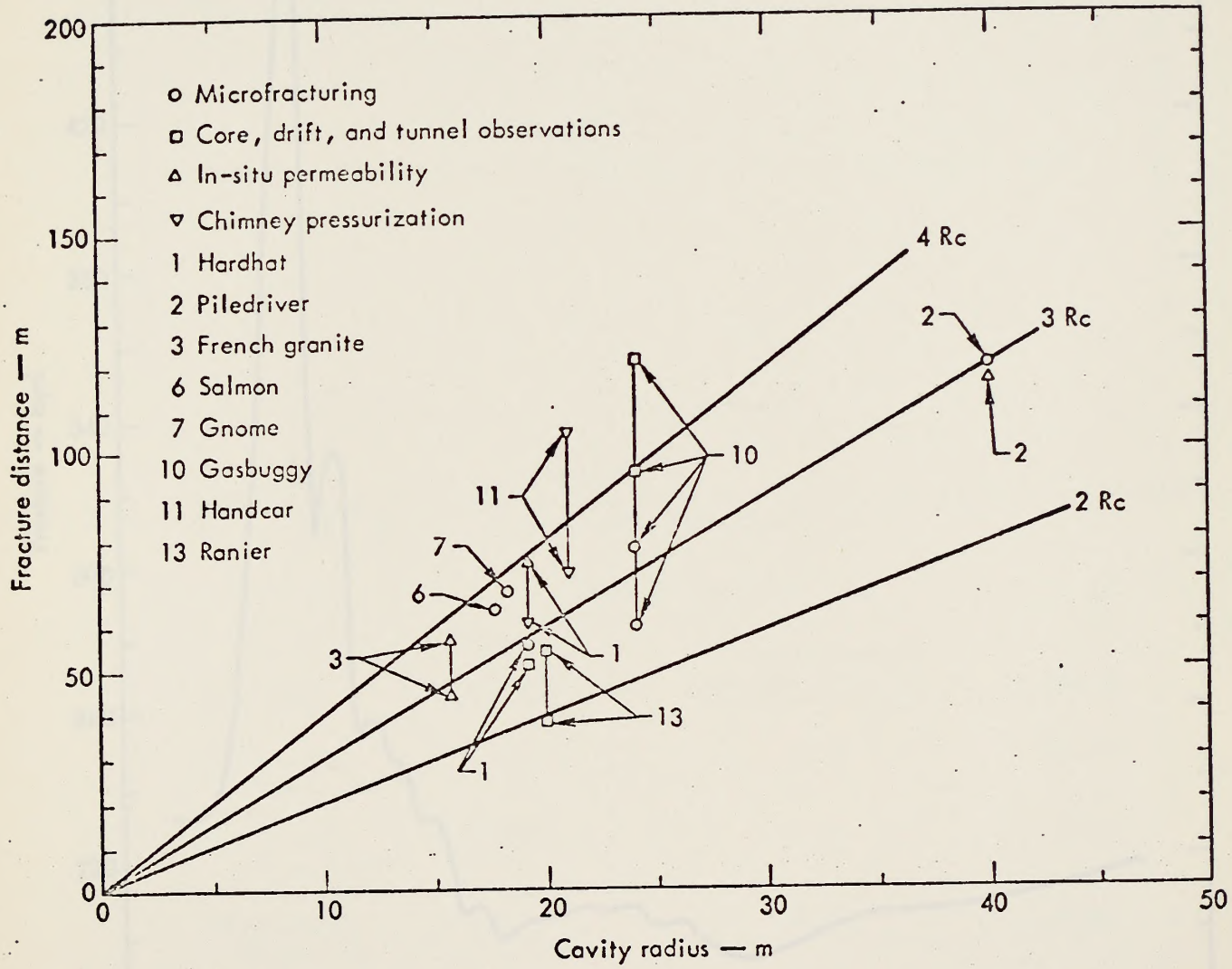



Fig. 5. Observed horizontal fracture distance.

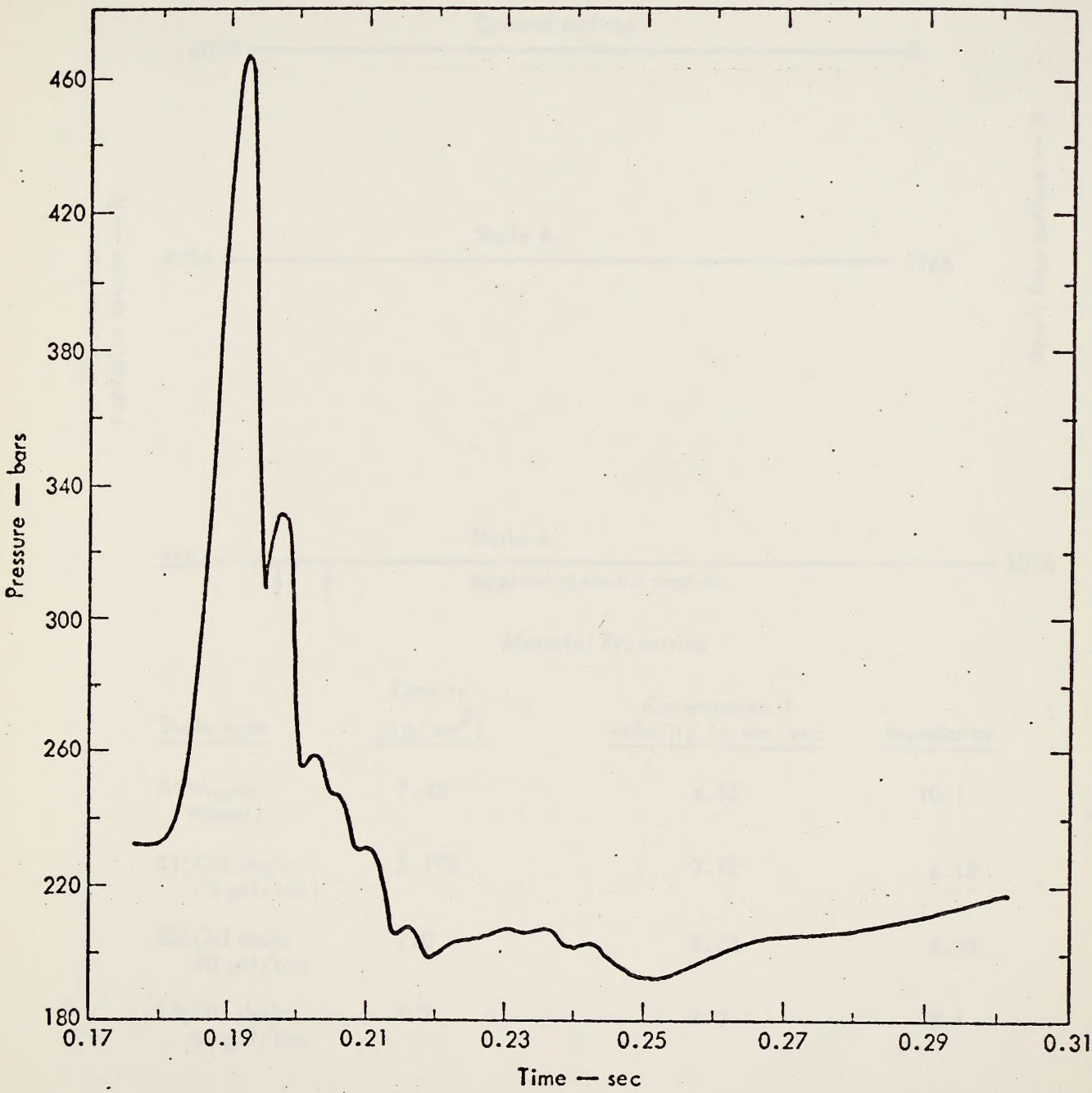
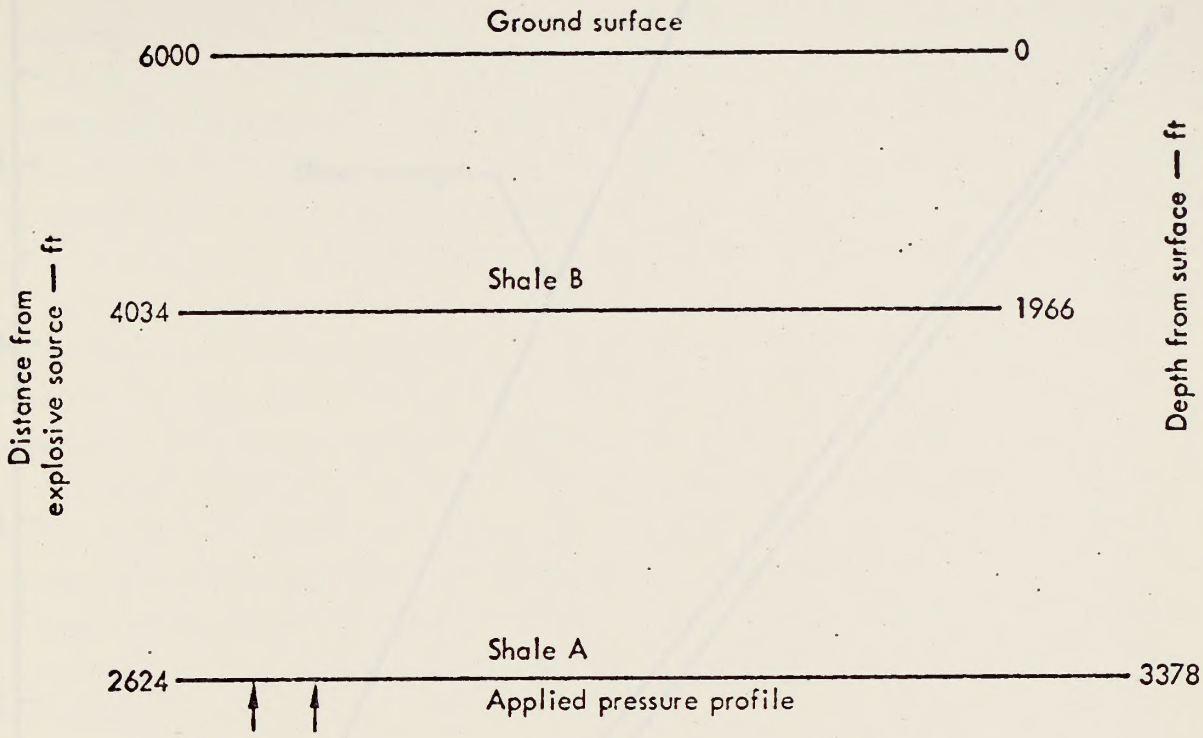



Fig. 6. Pressure profile at 800 m from 100 kt.




Material Properties

| Shale type | Density $\rho(g/cm^3)$ | Compressional velocity Cp km/sec | Impedance |
|---|---|---|---|
| A(Wagon Wheel) | 2.45 | 4.12 | 10.1 |
| B1(Oil shale 25 gal/ton) | 2.193 | 2.79 | 6.12 |
| B2(Oil shale 40 gal/ton | 2.0 | 2.23 | 4.46 |
| B3(Oil shale 60 gal/ton | 1.7 | 2.0 | 3.4 |

Fig. 7. Model for layer calculations.

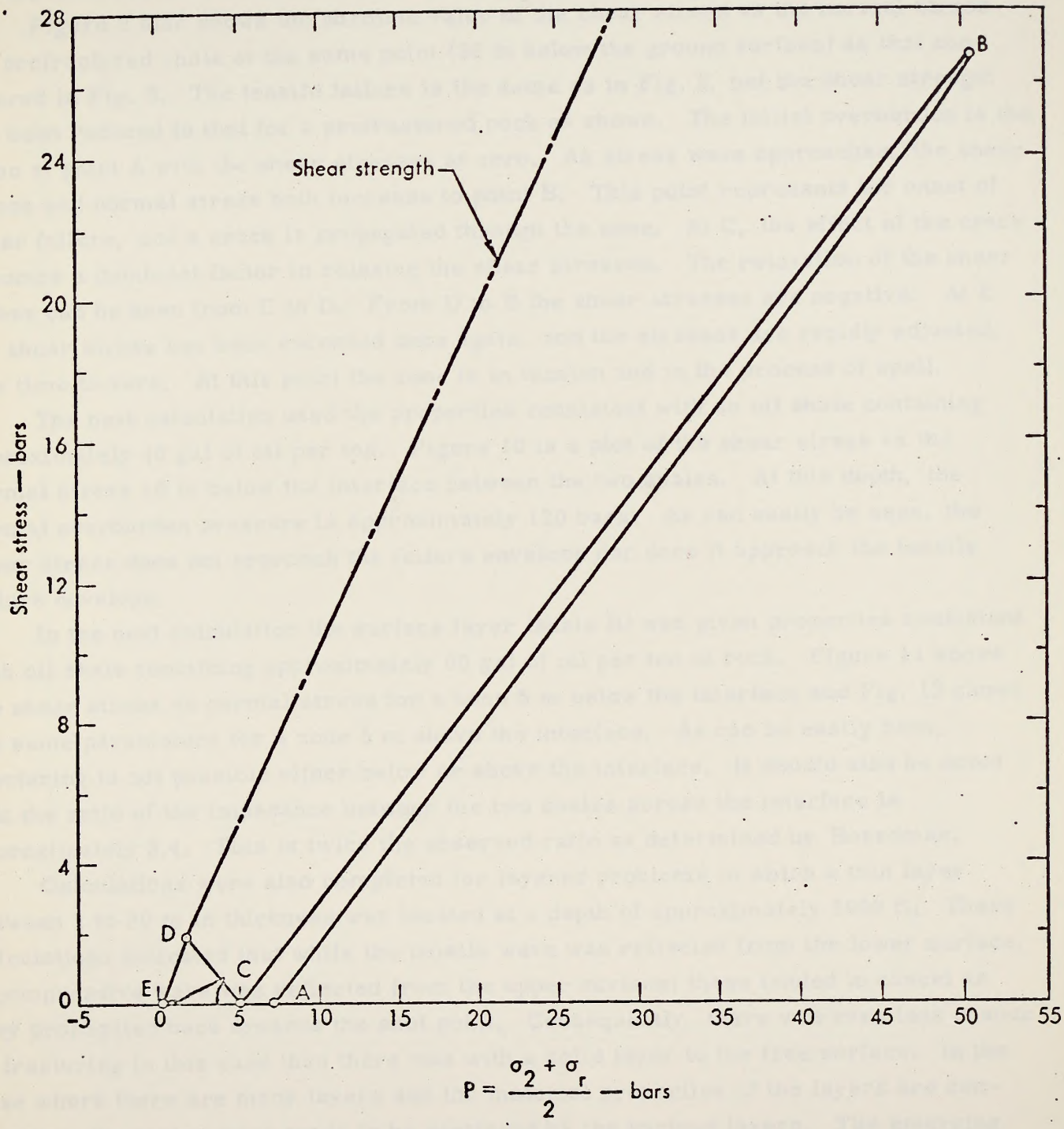



Fig. 8. Absolute value of the shear stress vs normal stress for unfractured shale 30 m below ground surface.

to point C, passing through zero. From C to D, the shear stresses are negative. At D they exceed the tensile strength of the rock; that is, they have exceeded the overburden stresses plus the shear strength of the rock. Consequently, the rock fails at D and the stresses then relax to zero at E. The zone is now in spall.

Figure 9 also shows the absolute value of the shear stress vs the normal stress for prefractured shale at the same point (30 m below the ground surface) as that considered in Fig. 8. The tensile failure is the same as in Fig. 8, but the shear strength has been reduced to that for a prefractured rock as shown. The initial overburden is the same at point A with the shear stresses at zero. As stress wave approaches, the shear stress and normal stress both increase to point B. This point represents the onset of shear failure, and a crack is propagated through the zone. At C, the effect of the crack becomes a dominant factor in relaxing the shear stresses. The relaxation of the shear stress can be seen from C to D. From D to E the shear stresses are negative. At E the shear stress has been exceeded once again, and the stresses are rapidly adjusted, this time to zero. At this point the zone is in tension and in the process of spall.

The next calculation used the properties consistent with an oil shale containing approximately 40 gal of oil per ton. Figure 10 is a plot of the shear stress vs the normal stress 10 m below the interface between the two shales. At this depth, the normal overburden pressure is approximately 120 bars. As can easily be seen, the shear stress does not approach the failure envelope nor does it approach the tensile failure envelope.

In the next calculation the surface layer (shale B) was given properties consistent with oil shale containing approximately 60 gal of oil per ton of rock. Figure 11 shows the shear stress vs normal stress for a zone 5 m below the interface and Fig. 12 shows the same parameters for a zone 5 m above the interface. As can be easily seen, fracturing is not possible either below or above the interface. It should also be noted that the ratio of the impedance between the two shales across the interface is approximately 3.4. This is twice the observed ratio as determined by Boardman.

Calculations were also completed for layered problems in which a thin layer between 1 to 30 m in thickness was located at a depth of approximately 2000 ft. These calculations indicated that while the tensile wave was reflected from the lower surface, a compressive wave was reflected from the upper surface; these tended to cancel as they propagated back towards the shot point. Consequently, there was even less chance of fracturing in this case than there was with a solid layer to the free surface. In the case where there are many layers and the material properties of the layers are contrasting, the stress wave tends to be scattered by the various layers. The emerging stress wave then has the characteristics of a stress wave propagated through a region whose material properties were the average of those of all of the layers.

Figure 13 illustrates the reflected and transmitted portions of the radial stress wave.

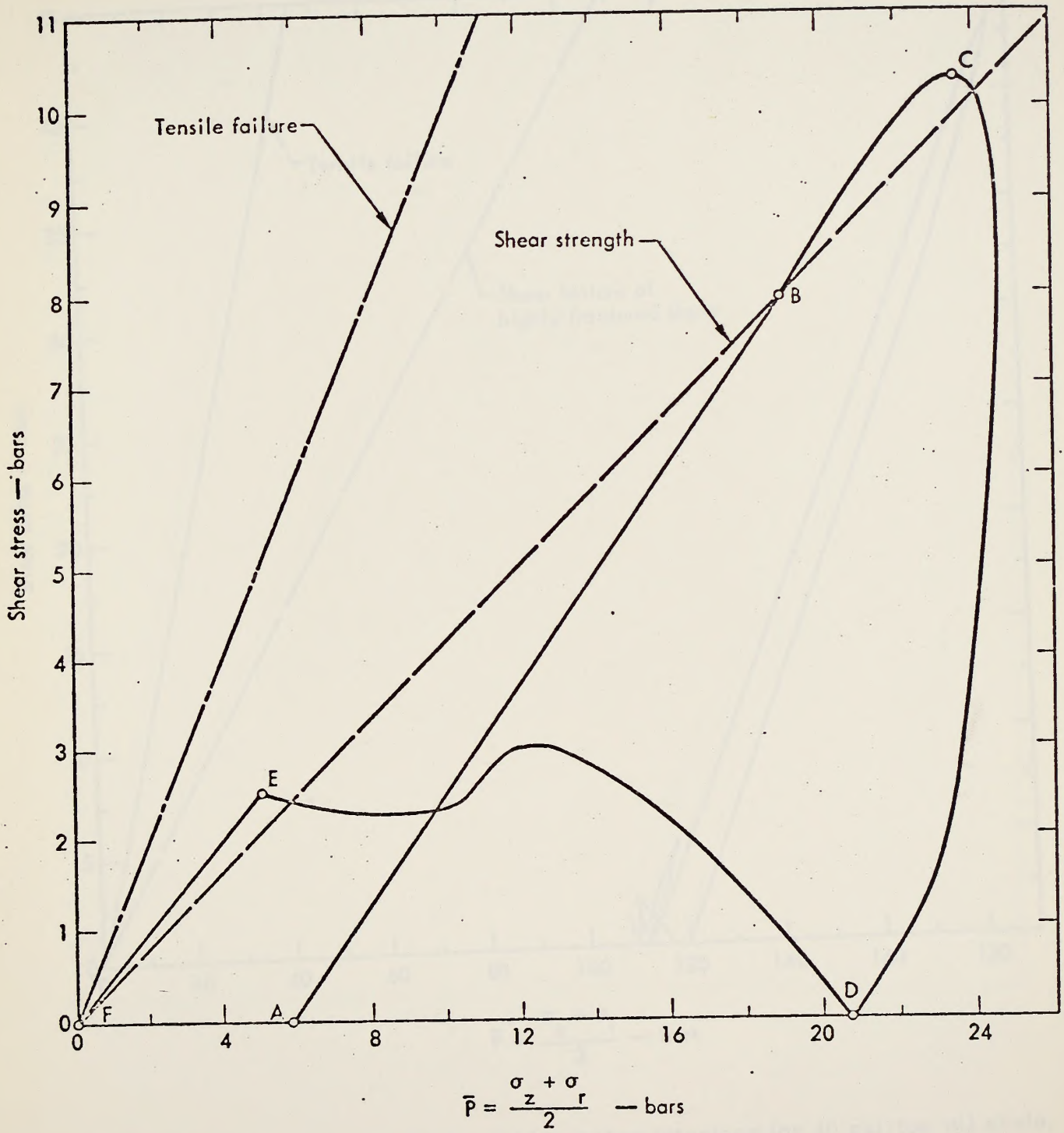



Fig. 9. Absolute value of the shear stress vs normal stress for prefractured shale 30 m below ground surface.

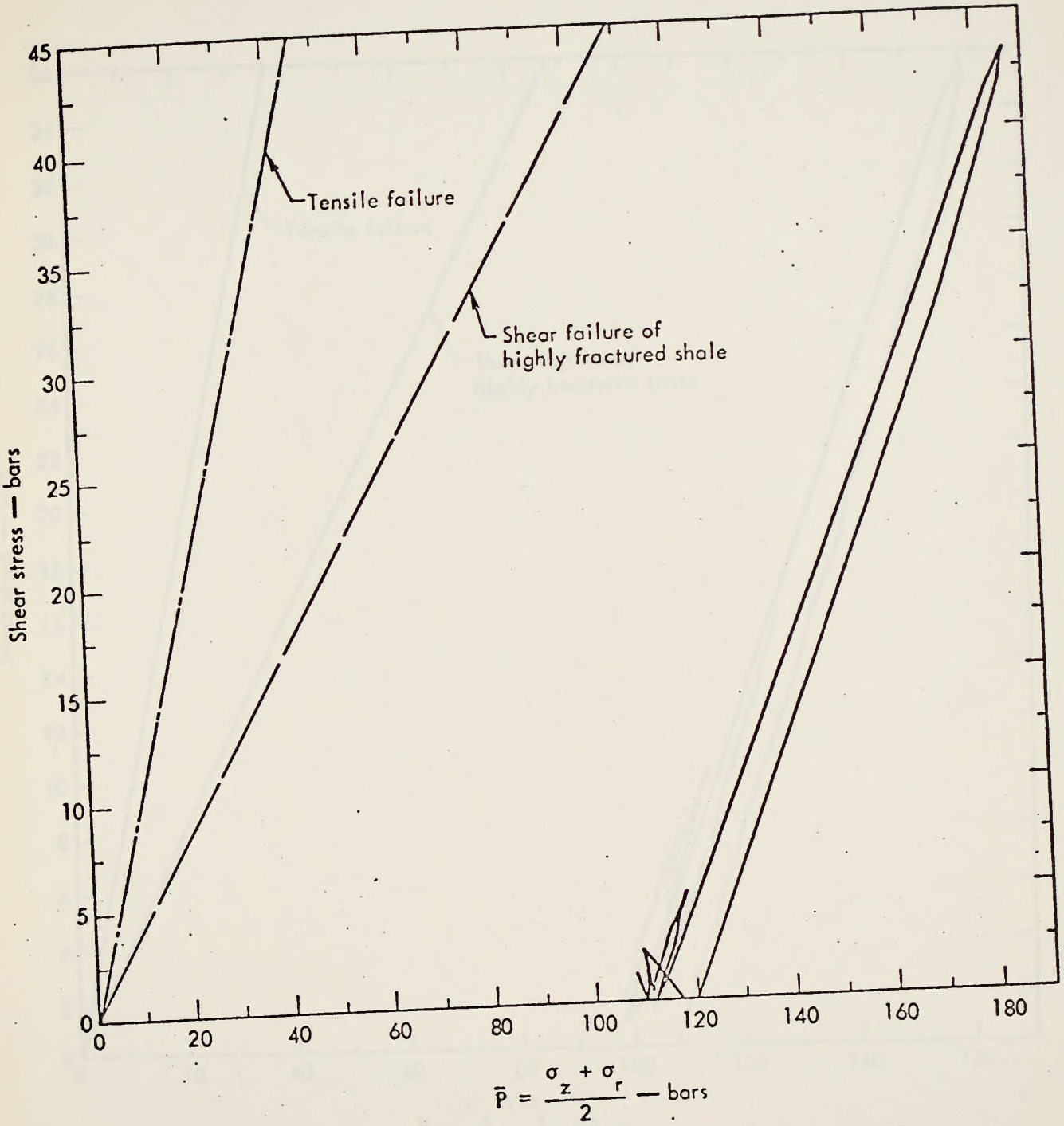



Fig. 10. Shear stress vs normal stress 10 m below interface for 40 gal/ton oil shale.

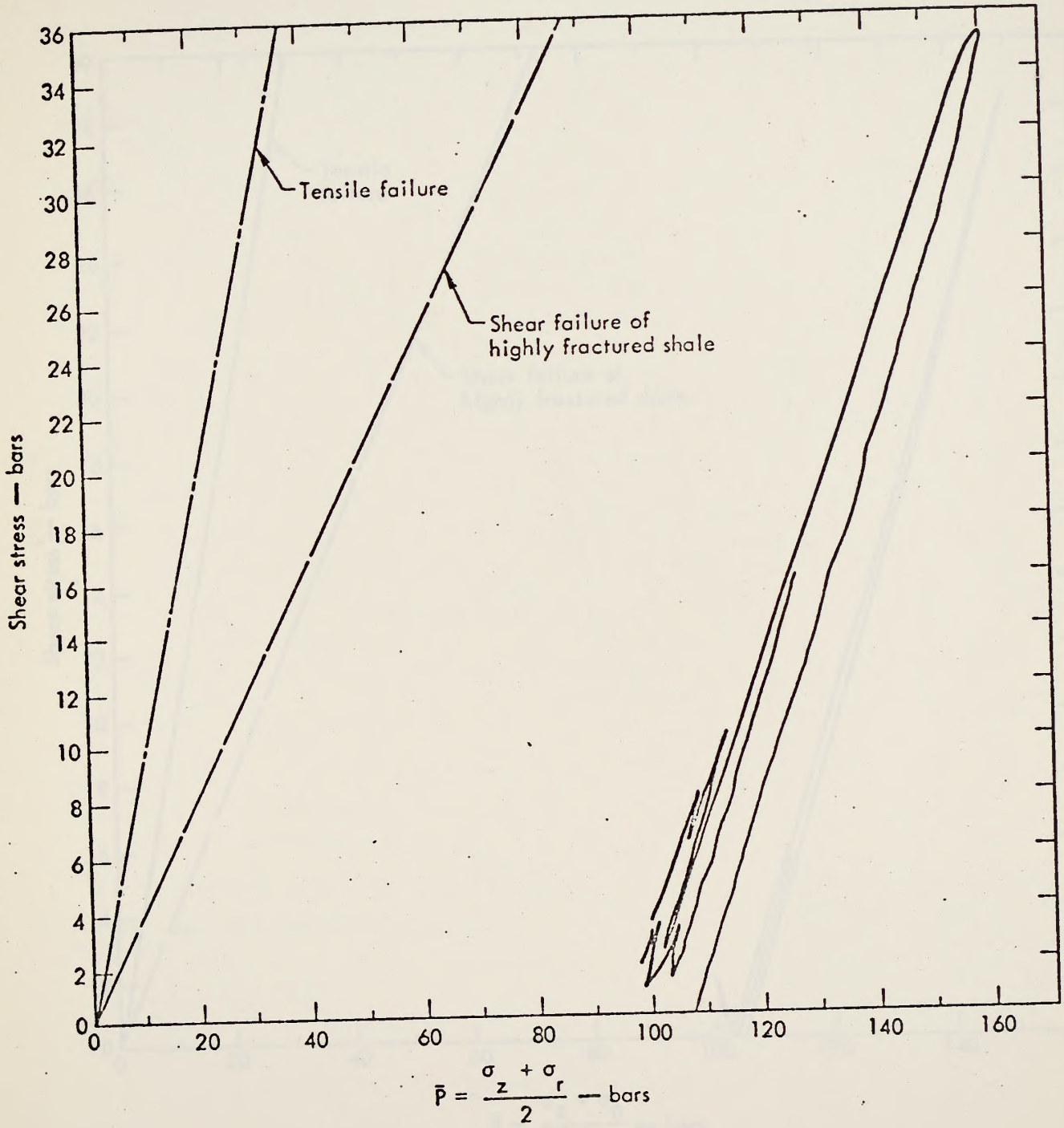



Fig. 11. Shear stress vs normal stress 5 m below interface for 60 gal/ton oil shale.

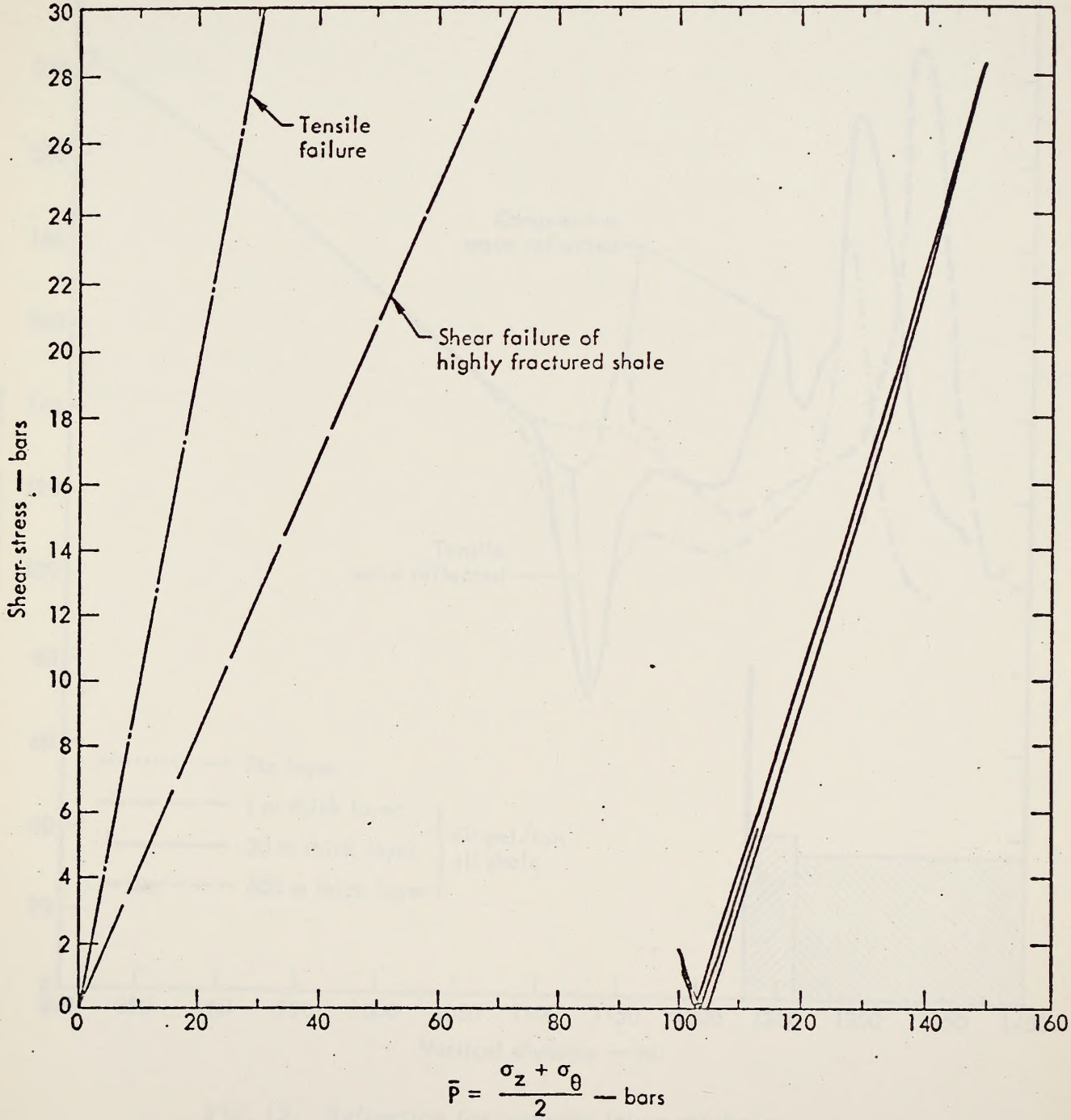



Fig. 12. Shear stress vs normal stress 5 m above interface for 60 gal/ton oil shale.

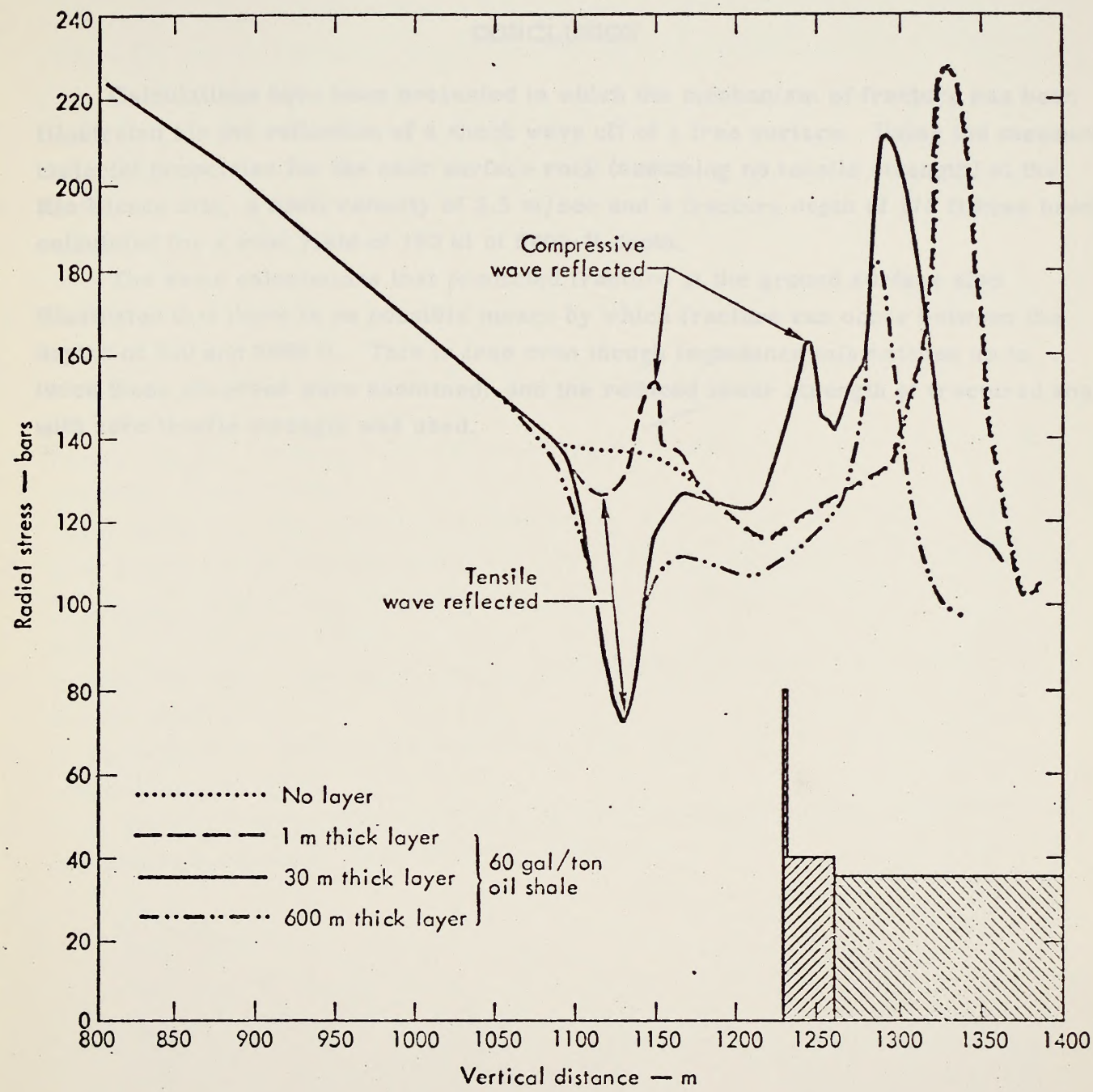



Fig. 13. Reflection for various layer thickness.

A 30-m zone reflects similarly to an infinitely thick zone except for the compressive wave returning from the outer surface of the layer. A 1-m zone will cause only a small perturbation on the existing stress field.

## CONCLUSION

Calculations have been presented in which the mechanism of fracture has been illustrated for the reflection of a shock wave off of a free surface. Using the measured material properties for the near surface rock (assuming no tensile strength) at the Rio Blanco site, a spall velocity of 2.5 m/sec and a fracture depth of 170 ft have been calculated for a total yield of 100 kt at 6000-ft depth.

The same calculations that predicted fracture at the ground surface also illustrated that there is no possible means by which fracture can occur between the depths of 360 and 5000 ft. This is true even though impedance mismatches up to twice those observed were examined, and the reduced shear strength of fractured shale with zero tensile strength was used.

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APPENDIX G

APPENDIX G

REPORT
SEISMIC EFFECTS PREDICTION
PROJECT RIO BLANCO
PICEANCE BASIN, COLORADO

FOR THE OIL SHALE CORPORATION

DAMES & MOORE

October 19, 1971

Mr. W. Alexander Blood
The Oil Shale Corporation
18200 West Highway 72
Golden, Colorado 80401

Dear Mr. Blood:

Reference: Project Rio Blanco

This letter is in response to your request for our evaluation of the seismic impact of the proposed Project Rio Blanco and subsequent shots on oil shale reserves and related resources in the area affected by the Project.

We feel that the project has a real and significant potential for damage, which we discuss in the attached report, "Seismic Effects Prediction, Project Rio Blanco, Piceance Basin, Colorado for TOSCO." The damage to the oil shale and related resources would mainly be in fracturing of the overlying oil shales, making their future exploitation expensive and hazardous.

We do not feel that CER Geonuclear has adequately provided for the anomalous, often extreme non-linear ground and free field motions frequently encountered in underground nuclear blasting.

Should there be any questions concerning the report, do not hesitate to contact us.

Very truly yours,

DAMES & MOORE

David J. Leeds
Senior Engineering Seismologist
Certified Engineering Geologist

James R. Swaisgood
Professional Engineer
State of Colorado #8262

JRS DJL rc

REPORT

SEISMIC EFFECTS PREDICTION

PROJECT RIO BLANCO

PICEANCE BASIN, COLORADO

FOR

THE OIL SHALE CORPORATION

## INTRODUCTION

Project Rio Blanco contemplates the proposed underground detonation of three 30-KT nuclear devices for the purpose of gas production stimulation by fracturing in a gas field in the Piceance Basin, Rio Blanco County, in northwestern Colorado. Project Rio Blanco is one of the Plowshare series for development of peaceful uses of nuclear energy. It is directed at improving oil and gas recovery over existing traditional methods of exploitation. Gasbuggy (1967) and Rulison (1969) were the first of the Plowshare series. Rio Blanco and Wagon Wheel are proposed follow-ups. The first phase of the project plans a total of three 30-KT shots fired simultaneously, to be followed by 120 to 240 shots throughout the unitized area.

It is presumed that the detonation can be safely contained and that no nuclear products will be released into the atmosphere. It is also presumed that the economic aspects are such that from the point of view of the developers, the surface engineering physical effects will be within acceptable range,

the subsurface fracturing adequate to release the desired quantities of otherwise non-recoverable gas, and that the costs versus increased production are such that the project is economically feasible and, in the long run, profitable.

Calculations claimed by the developer on the basis of empirical experience on somewhat similar shots indicate that both subsurface and surface ground motions will be generated with predictable and acceptable results. We are impressed by the thoroughness of the "homework" by the several consultants but must point out that the predictions are based on average values extrapolated out of range of experience.

These techniques are generally acceptable when the total picture is examined but can be erroneous when applied to a specific location. The methods tend to discard the extreme values and embroidery effect and only utilize observations which exhibit little deviation from the norm. Yet the actual ground motions of extreme values may be from seven to ten times the predicted ground motions. Explanations for this difference vary from instrumental error and focusing to coupling and non-cooperative geology. In fact, ground motion can only be imperfectly predicted. The accuracy of prediction improves when conditions are exactly repeated. Since that situation does not exist in nature, some variation in response at a specific site must be expected. The accuracy also improves if the empirical behavior is applied to

sites which have dynamic properties analogous to those of the experimental data and if the device (yield) is nearly the same and fired in analogous shot point geologic conditions (material properties and depth). Again, since analogous conditions do not exist and yield is only of limited predictability, extrapolation of the empirical "laws" has a built-in uncertainty. Also, application of a general law to a specific site can lead to even more deviation.

An area of uncertainty also exists in the possible migration of saline waters in blast-produced fractures into potable waters or into the Colorado River drainage system. This potential hazard is not treated in this report.

TOSCO operates, or plans to operate, both surface and underground facilities in the Piceance Basin. Project Rio Blanco will, along with its planned objective, generate large ground motions above the shot point within the oil shale resources at a moderate distance below ground (free field) and on the surface many miles from SGZ (surface ground zero).

This report examines the possible seismic effect on oil shale and related resources within the range of the proposed Rio Blanco shot. The principal effects considered are fracturing of the minable oil shales immediately above the shot point.

## PROJECT DESCRIPTION

Essential details of Project Rio Blanco and the closely related forerunner shots from which predictions are made are described below:

| | RIO BLANCO | RULISON | GASBUGGY | LONGSHOT |
|---|---|---|---|---|
| Location | Piceance Basin | Piceance Basin | Rio Arriba Co., New Mexico | Amchitka |
| Date | ? | 9/10/69 | 12/10/67 | 10/29/65 |
| KT | 3x30 | ~ 40 | 29 | ~ 80 |
| Magnitude | (5.0) | | 4.35 | 5.9 |
| Depth, Ft. | 5900<br>6350<br>6900 | 8430 | 4240 | 2300 |
| Coupling | | | | Extra good |
| Geology | Mesa Verde Formation | Mesa Verde Formation | Pictured Cliffs Sandstone - shale San Juan Basin | Andesite |
| Ground Motion, g | | | | |
| Surface | | | | 26 |
| SL 6300' | | (10) | | 2.8 |
| SL 8600' | | (10) | | 0.88 |
| 30,000' | (1.0) | 0.5 | | |
| 50,000' | (0.5) | 0.2 | | |
| In-situ Gas Pressure, psi | 3500 | | | |
| Free Field Frequency, Hz | (3) | | (5) | |
| Observation Range, km | ---- | 3.5~300 | .75~90 | .4~13 |

( ) Parentheses indicate estimate

## SEISMIC EFFECTS

Several types of seismic effects are expected from deeply buried nuclear (or chemical) explosions:

Free Field Motion:

This term describes the actual physical motion generated in the rock mass by the passing shock wave. Close to the detonation, there is a plastic zone where deformation is complete; then, there is an elasto-plastic zone where some residual permanent deformation remains after the passing of the shock wave. The larger region, the subsurface, behaves elastically.

Surface Motion:

Surface motion away from SGZ is usually twice the free field motion. This amplification of the subsurface wave is due to the addition of the incident and reflected wave.

Spall:

On the ground surface above the shot point, motions are such that accelerations exceed gravity and the ground surface or free face actually heaves upward. The depth and range of spall are of interest.

Fracture:

Fractures are minute permanent displacements, usually along joints, in the elasto-plastic or rupture zone. The zone of fracture grades from practically no separation to gross fracture. Since there are many joints present in the native shale, the material lends itself to separation.

Recorded motion or response is governed by many factors which tend to complicate the prediction of seismic effects:

Station Corrections:

Station corrections, or a consistent variation in recording at a given site, have been observed to yield differences in magnitude units of from 0.7 to 0.8. This represents a difference due to site conditions at the recording locations.

Azimuthal Correction:

Theoretical azimuthal differences in response are related in earthquakes to mechanism. In a nuclear shot, the differences appear to be related to the geologic environment and geometry of the path.

Coupling:

The effectiveness of transfer of mechanical energy into the ground is called coupling. This varies with size of the chamber, depth of burial, formation pressure, water table, and physical properties of the containing rock. Coupling is usually an unknown, although Long Shot appears to be an upper bound.

Yield:

Yield is the energy output of the shot rated in terms of the seismic effect of 1000-ton units (KT) of high explosives. Yield has only limited predictability,

depending upon the efficiency of the detonation. (Ref. - Springer and Kinnaman.) With experience on a given type device, predictability of yield is no better than plus or minus 20 percent. Little experience of AEC is indicated in the firing of shots of Rio Blanco size. Published data shows many in the 20 to 200 KT range, but very few explicitly of 30 KT size, and no data on multiple shots has been published. (Ref. - Springer and Kinnaman.)

Geometry:

Little is known of the additive effect of several devices. It must be assumed, at least for distances where distance from SGZ approaches slant range, that the ground motion of simultaneously fired shots is additive. Close in, there may be some absorption of energy as the shock wave of the deeper devices passes through the overlying fracture zones. For conservatism, the effect of three separate shots at specific distances should be added.

Scaling Laws:

Each of the several researchers utilizing the data of previous shots has derived scaling laws. These laws permit the extrapolation of empirical results to predict future results. Some are careless with units

and some with the selection of data from which the laws are derived. Another hazard is in the misapplication of the law by extrapolation well beyond the range for which it was written. With log-log plots the degree of permissible extrapolation is deceptive.

Focusing:

Many explanations have been developed to explain aberrant results in seismic predictions or to explain anomalous earthquake effects. A few cases are on record (and as the geologic picture becomes more complete, others will satisfy) where optical laws are followed by the seismic waves. In these instances, waves may be focused and energy concentrated. Note the paper by Jackson for a theoretical explanation. We have examined several cases where the mechanism is valid. In 1952 in the Kern County, California earthquake, we attributed the loss of the Paloma Cycling Plant to high ground motions caused by focusing.

Site Characteristics:

Material properties at the point of detonation affect coupling or energy transfer, and properties enroute (path) control the energy delivered to a specific site. Properties such as density, shear modulus, and

stratigraphy (layer thickness) control the response of a site (Ref. - Duke & Leeds.) The theory of surface amplification, originally proposed by the Japanese, was further developed in the United States. Recent NTS studies (Ref. Alcock) have documented its applicability to the prediction of ground motion.

## EARTHQUAKE

The northwest portion of Colorado has been reasonably free of large or damaging earthquakes. There are advantages, in construction and mining practice, to this desirable state. Less care need be taken and less money expended in aseismic design of all engineering construction, from housing to mines, than in the more seismically active zones of the west. On the negative side, however, is the increased vulnerability to seismic damage due to this neglect, the lack of experience (or "shakedown"), and the not too remote possibility of the triggering of larger natural earthquakes by the artificially induced ground motion.

Earthquake epicenters in the Piceance Basin area are shown on Plate 1. This map was drawn from the Hypocenter Data File of the National Ocean Survey, NOAA. The lowest magnitude computed on this list is 3.1. Events smaller than that, or without a computed magnitude, are indicated as "microearthquakes." This term is not appropriate, since many

of the events are much larger but lack records adequate for magnitude determination, or interest in the computation. Of the nine plotted events occurring from 1941 to 1960, only two had computed magnitudes (5.25 in 1950 and 5.50 in 1960). After the establishemnt of the world-wide standard seismograph network in 1961, the level of perceptibility lowered. In the 10-year period, 86 events are plotted, only 32 of which are without magnitude determinations. Obviously the map indicates little more than 10 years of record and should not be considered representative of the seismic potential for the area. The minor seismicity indicates that the area is not completely at rest.

Experience in the southwest part of the United States indicates that the triggering of natural aftershocks following a deeply buried nuclear explosion is a real hazard. (Ref. - Krivoy & Mears, Coucher et al, Hamilton et al.) These aftershocks can be considered sympathetic events of nearby seismogenic zones which have not had stress relief. To date, the aftershocks have been smaller than the initial event, but their locations have been remote. Fault displacement can also result from underground explosions. (Ref. - Dickey.)

Possible chimney collapse at the surface has not been treated. Surface collapse has developed months and even years after the shot. Collapses have generally been from shallow shots (less than 1,000 feet), but some larger deep shots (Greeley 3,985 feet) collapsed months after the shot. Small earthquakes could act as triggers for these events even if they did not occur principally.

## SURFACE GROUND MOTION PREDICTIONS

The prediction of Rio Blanco surface ground motion is based on the extrapolation of experience gained in the nearby Rulison event. Only two close-in observations are reported - - at 3,500 meters (10,800 feet) and at 7,000 meters (21,600 feet). (Ref. - Loux, Figure 5.) The 3,500-meter slant range observation was approximately one-third the value predicted. The 7,000-meter ground acceleration was recorded at twice the value predicted.

We have utilized the Rulison data, selecting high observed data points to define an attenuation curve and doubling the value to account for the higher yield of Project Rio Blanco. This may appear conservative and probably is for locations on exposed rock. The higher points utilized probably represent observational locations in thick or more responsive soils. The differences between the high points of observational data used for our curve and the least squares set of the observed Rulison data represent amplification due to site conditions. Anomalous conditions, beyond those represented by Rulison sites, would be expected to develop even higher ground motions.

Observed peak particle resultant vector acceleration (Loux - Figure 5) is shown as Plate 2. Our predicted Rio Blanco ground motion is shown on Plate 3. As indicated in the preceding paragraph, our curve is a high ground motion fit of Rulison data, doubled to account for yield. It is applicable on the surface only at slant distances greater than about 3km, or 10,000 feet.

## FREE FIELD PREDICTIONS

Free field motion predictions at SGZ by the project operator presume that the device will be exploded 3,100 feet below the oil shale and that the shale will receive the effective impact of the first 30 KT detonation at this distance. No mention is made of the possible enhancement of that shock by the arrival of the second and third detonations approximately 0.05 and 0.125 seconds later.

There are no available experimental data to validate the claimed performance. Linear extrapolation from high explosive modelling yields results which appear to comply. The comparisons made by CER Geonuclear are of the acceleration at equivalent distances due to dynamite and nuclear shots. Since these have a different spectral response at the various distances from the two sources, it is not felt that the comparisons are justified or applicable. Comparison is only made in the acceleration mode of ground motion. The frequency at which the comparison is made should be stated, as well as its duration.

The picture is still far from complete since the damage criteria is not defined. CER calculations assume the failure is in shear. Tensile failure is more important by far close in. Studies by CER Geonuclear indicate that there will be no permanent faulting or jointing. The fracturing need not have accompanying permanent displacement. Any tensile fracturing in the shale will weaken its static properties and render it more difficult to mine.

Much more needs to be known about the behavior of shale at the elastic to elasto-plastic motion levels. The criteria for damage must be defined. It is felt that as motions approach 1 g in the shale mass that the passage of the shock wave opens up small fractures, however brief the period may be. These small tensile fractures or joints, even without permanent distortion, establish planes of weakness in the shale mass that affect their future behavior.

Tests should be made on samples of identical material withdrawn from the formation, then repeated on the same material after it has been exposed to known accelerations. Static compression, tension and shear tests and dynamic velocity tests should be performed. From this experience, estimates can be made with more confidence that at the present time.

## SPALL ESTIMATES

Spall estimates are based upon a presumed homogeneity and competency of the overlying shale. Unfortunately, neither of these conditions exist except in laboratory-size specimens. These estimates indicate that horizontal fractures could possibly be opened to a depth of 320 to 360 feet. The calculations and method are not shown. Since oil shale exists in the Parachute Creek member of the Green River formation at depths of from 129 to 500 feet and in the Mahogany Marker at

depths from 190 feet to 864 feet, this potential of damage seems perilously thin. No attention is given areas of topographic relief where distance from surface varies. The CER Geonuclear estimates are stated to be conservative, but no account has been indicated for several of the variables known to be present. The physical properties of the site, such as velocity and density, probably vary no more than plus or minus 10 percent, and the yield no more than plus or minus 20 percent. Local fractures and topography could further distort the effect -- both at the original Rulison site and at Rio Blanco. Further, there is no well-defined description or criteria of either fracture or spall. A total depth of spall of up to twice that predicted is not unreasonable.

An indication of the complexity of the area is indicated by the portion of a joint pattern map, Plate 4, taken from unpublished USGS data by F. A. Welder, 1970. These joints are only those inferred from aerial photographs. Mine inspections by the authors of our report reveal that the Welder map is merely a gross simplification of the joint/fracture pattern existing subsurface. The joints visible in the photos average two per mile. Spacing subsurface is on the order of tens of feet or less. Pronounced horizontal bedding planes are also present, which are responsible for the amazingly smooth floors and roofs of the oil shale mines.

The rock bolting programs in effect in the mines are additional evidence of the lack of structural integrity of the oil shales.

Uncertainty also exists in the prediction of spall and fracture.

SEQUENTIAL FIRING

In normal mining operations, it is standard practice to reduce the seismic impact by "delay" or sequential firing of rounds of powder. The total load is divided into many separate shots, using caps with suitable delays, so that instead of the total tonnage detonating instantaneously, only small fractions of it go in sequence, with microseconds of delay between charges. The effect of this is to generate ground motions only a small fraction of that of an instantaneously fired shot. There is no objection to this practice in gas fracturing. The only problem is that at the present time "hardened" nuclear devices do not exist. They are under development by the AEC and there is promise of their availability within a few years if the research programs continue to be funded.

For efficiency in gas recovery, future shots will probably be placed in each of many horizons. A single boring might have as many as five devices in it, each a nominal 30 KT. For the foreseeable future, this would generate intolerable free field and ground motions. With 320-acre spacing, by the

time the basin had been completely developed, the entire area would have been exposed to ground motions of more than 1 g several times.

It would seem prudent to delay the gas exploitation of the basin until first, the overlying oil shale resources are depleted, and second, until a hardened device is available. The basis for this is the non-interference of the gas reservoir by oil shale operation, and the much reduced free field and ground motions generated by delay (sequential) blasting. Shots even larger than those presently planned would be permissible for each horizon.

## SUMMARY

Oil shale and related resources have been examined with respect to the possible seismic impact of Project Rio Blanco. While the consultants have accomplished a great amount of serious study and in general have properly applied both empiricism and theory, the "in general" is the deceptive feature of the whole operation. Effects must be considered specifically, or in particular. When they are, there is an increase in the degree of uncertainty, pointed out by all of the researchers. All of the researchers have warned of the uncertainties in the application of empirical data and the hazard of its direct application.

In detail, there is some chance that fractures will be caused in the oil shale immediately above the shot. The degree of damage is not determinable.

Should the project be implemented, monitoring of effects on the oil shale resource should be accomplished.

We are in no position to evaluate the total worth of the project in terms of effects planned versus surprises; costs anticipated versus unexpected costs; returns/profitability of major objectives versus long-term side effects. Some attention should be given the additional mining costs that could be imposed by shale fracture damage.

We are immediately struck by the thought that the present shot in Piceance Basin is a forerunner for a large number of multiple shots to follow -- a few in a second round, then two dozen more, and as many as two per square mile before the gas resources of the basin are completely exploited. This exploitation would be at the cost of potential and possibly very real damage to the minability of the overlying oil shale, as well as surface properties. The damage would be in the form of increased fracturing of the shales which would make mining difficult, expensive, and hazardous. The increased recovery expense could be the margin of economic feasibility for the oil shale industry.

We do not feel that CER Geonuclear has demonstrated that Project Rio Blanco is without seismic hazard to oil shale and related resources, including TOSCO interests.

The following are attached and complete this report:

Plate 1 - Piceance Basin Epicenters

Plate 2 - Observed Peak Particle Resultant Vector Acceleration (Rulison after Loux)

Plate 3 - Predicted Project Rio Blanco Ground Motion

Plate 4 - Joint Pattern

References R-1 to R-6

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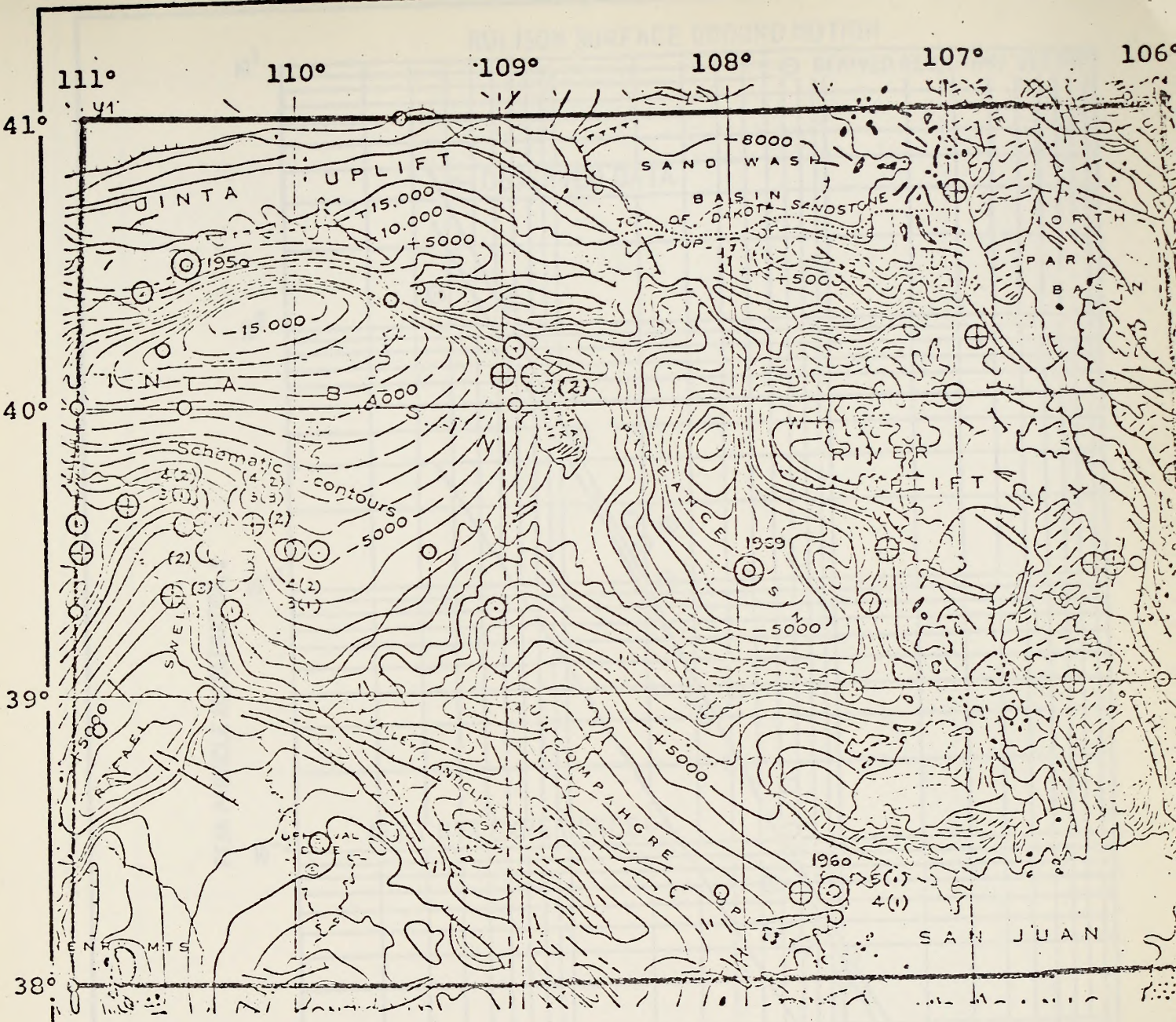
JRS DJL rc

October 19, 1971
Denver, Colorado




KEY:

- o Microearthquakes
- ○ 3.0 - 3.9
- ⊕ 4.0 - 4.9
- ◎ > 5.0

NOTE: Microearthquakes at Price, Utah not shown

PICEANCE BASIN
EPICENTERS

N.O.S. Hypocenter

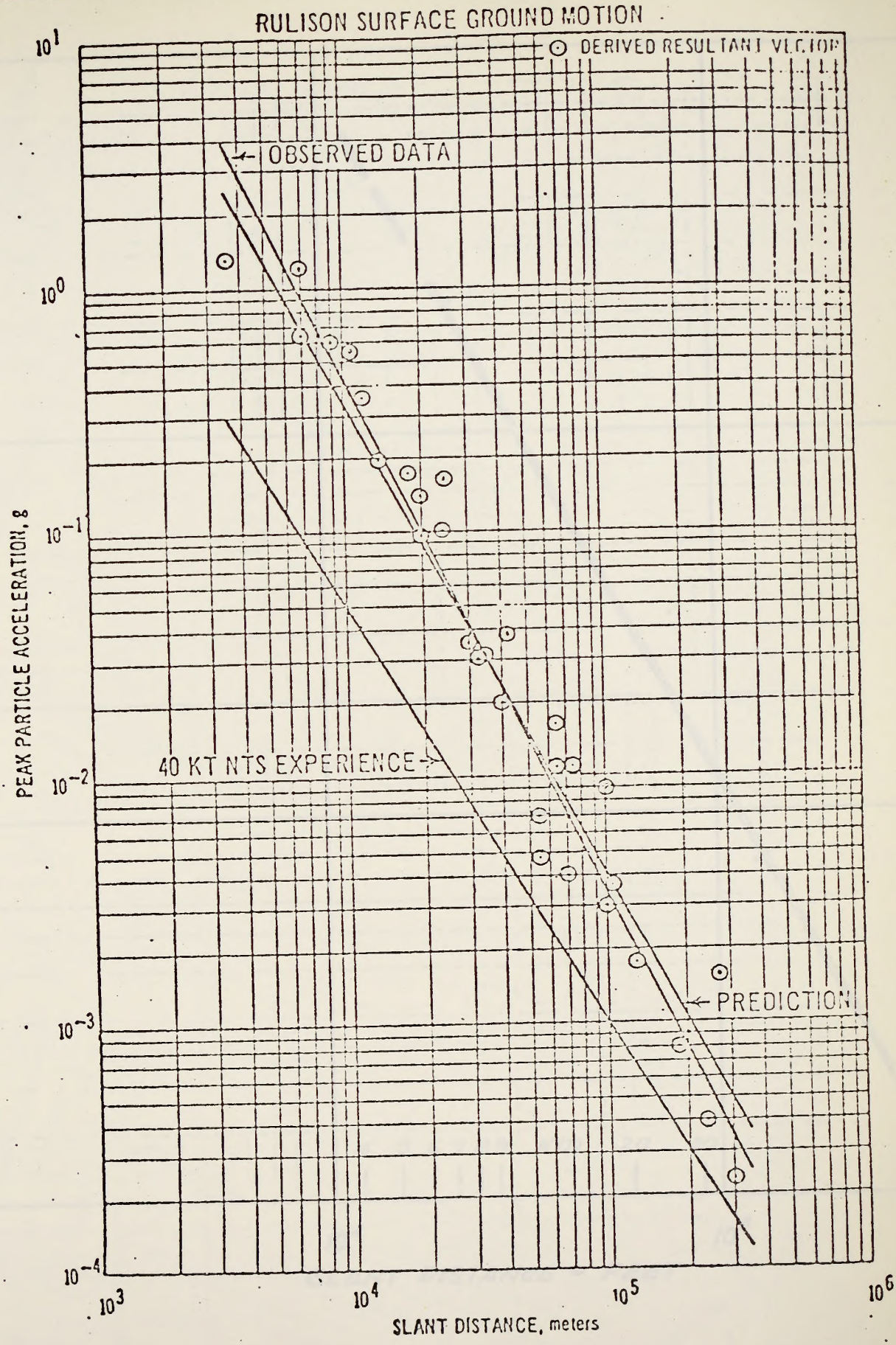



Figure 5. Observed Peak Particle Resultant Vector Acceleration

P. C. Loux
4th Plowshare Symposium 1970

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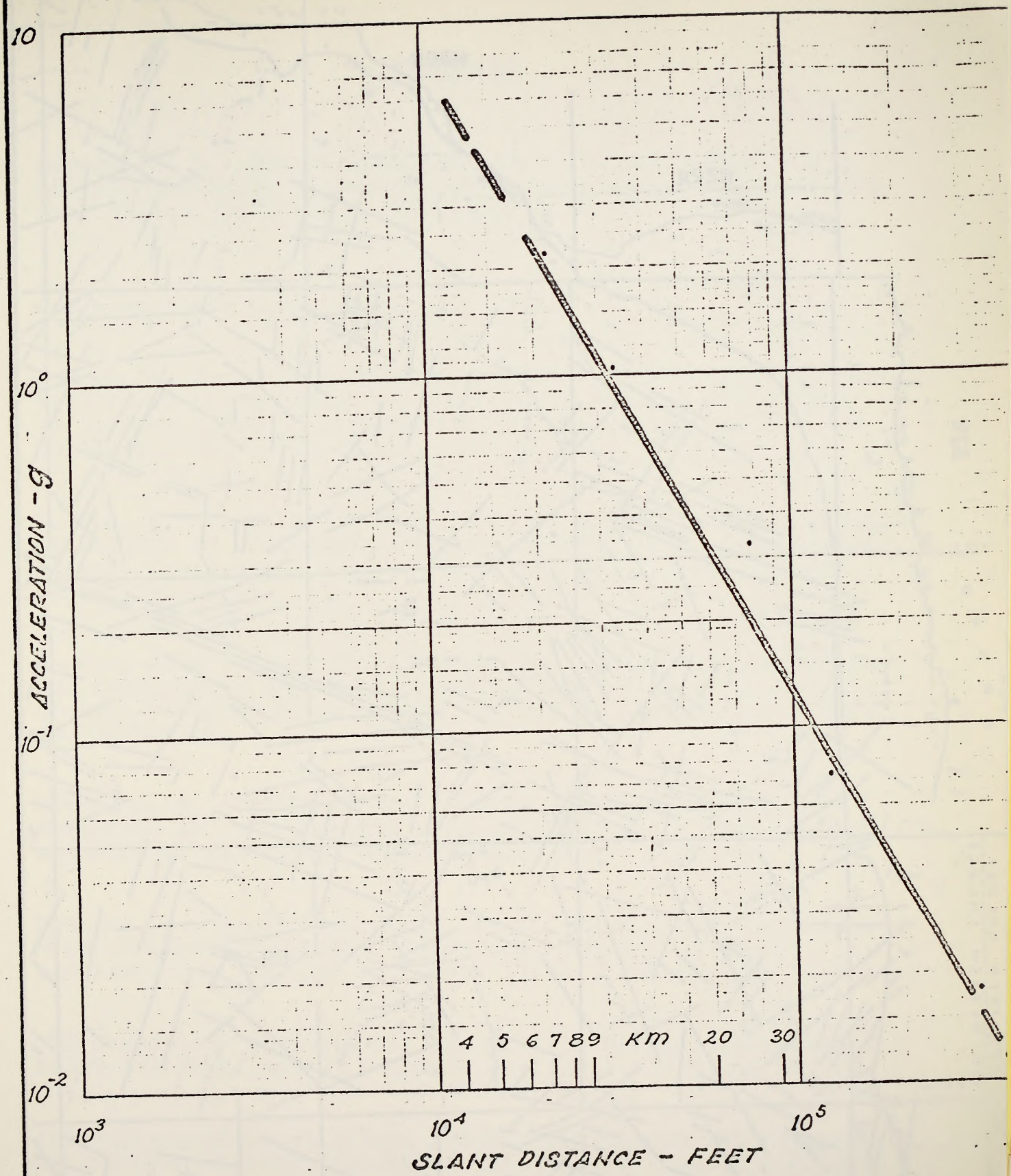


PREDICTED PROJECT RIO BLANCO GROUND MOTION

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APPLIED EARTH SCIENCE

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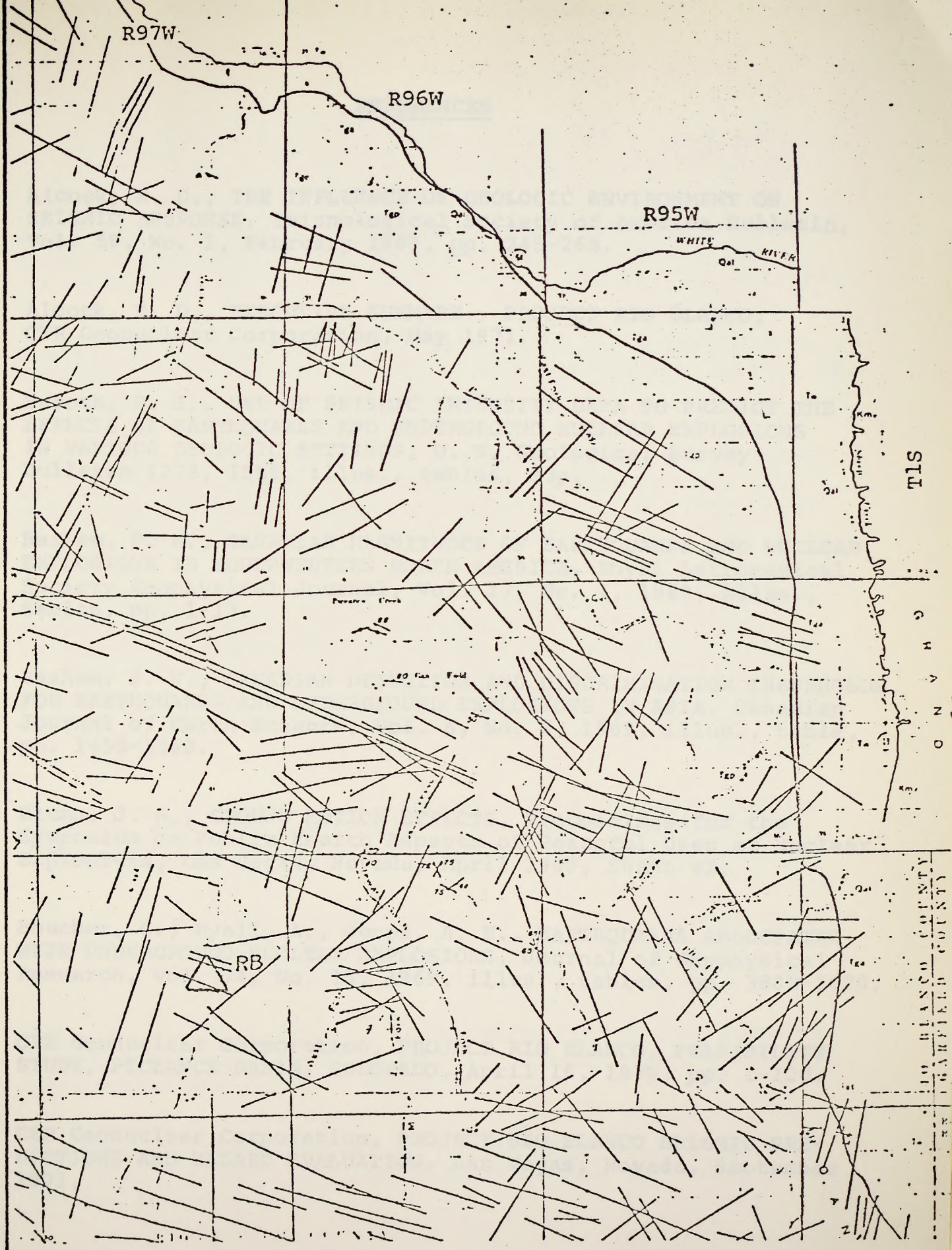


JOINT PATTERN

after F.S.Welder
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APPENDIX H

APPENDIX H

# THE STRESSES TRANSMITTED TO THE ROCK FORMATION OVERLYING THE PROPOSED RIO BLANCO NUCLEAR SHOT AND POSSIBLE INDUCED FRACTURE

A report prepared March 29, 1972 at the request of Dames & Moore, Consulting Engineers in Earth Sciences, by

R. Burridge


## ABSTRACT

Using simplified but reasonable assumptions concerning the mechanical properties of the rock formations overlying the proposed Rio Blanco shot point, estimates of the level of compressions in the direct shock wave and tensions in the reflected tensile pulse are made using ray theory and linear elasticity.

Following Terhune (1971) we assume as input the pressure profile computed for a distance of 800 meters from a 100KT shot fired in Wagon Wheel shale at a depth of 6000 feet. We estimate that net tensions both in the horizontal and the vertical directions may penetrate to depths up to about 1200 feet, depending upon the detailed mechanical model assumed for the upper 2000 feet. This differs from earlier estimates in that previous workers have predicted that no tensions would penetrate below 360 feet. But, whereas previous studies have been based upon the assumption of zero tensile strength in the upper layers of rock (Holzer & Emerson (1971); Terhune (1971)), no such assumption was made in the present work.

Non-zero tensile strength in these upper layers allows tensions to be transmitted to underlying zones of mechanically weak rock such as the oil rich Mahogany Zone, which is known to be highly jointed and fractured, and susceptible to further tensile fracturing.

The upward-going pressure wave may also cause damage by extending existing fractures if these contain water under pressure, since the water will support a part, or perhaps all, of the pressure which would otherwise be supported by the solid faces of these fractures and thus reduce the frictional resistance to sliding across these joints. No damage to intact or dry rock is expected to be caused by the up-going pressure pulse in the oil shale deposits except in so far as existing fractures are extended into the intact rock.

## 1. The Idealised Mathematical Model

Following Terhune (1971), we shall study the propagation of an elastic pressure wave which emanates from a 100KT explosion 6000 feet deep in a material we shall call Shale A. Above a depth of 1966 feet below ground level there is a rock with different mechanical properties, which we shall call Shale B. In order to make the problem tractable, these two materials are supposed to be uniform, isotropic, and elastic with the properties listed in Table 1 where several different materials are assumed for Shale B, each one used for a separate calculation. Shale A remains the same for all calculations (see Figure 1). Our basic

assumptions differ from Terhune's only in that in our mathematical model the surface layers have sufficient tensile strength to support the reflected tension wave, whereas he assumed zero tensile strength in the upper 2000 feet. See Terhune (1971) for a justification of the model. We also differ in the method of calculation.

When Shale B is taken to be of type B1 (see Table 1) the model is most relevant to the expected structure at the Rio Blanco site.

TABLE 1 (AFTER TERHUNE 1971)

| Shale Type | Density (gm/cm$^3$) | Compressional Velocity km/sec | Impedance |
|---|---|---|---|
| A (Wagon Wheel) | $\rho_A = 2.45$ | $\alpha_A = 4.12$ | $I_A = 10.1$ |
| BO = A | $\rho_{BO} = 2.45$ | $\alpha_{BO} = 4.12$ | $I_{BO} = 10.1$ |
| B1 (Oil Shale 25 gal/ton) | $\rho_{B1} = 2.193$ | $\alpha_{B1} = 2.79$ | $I_{B1} = 6.12$ |
| B2 (Oil Shale 40 gal/ton) | $\rho_{B2} = 2.0$ | $\alpha_{B2} = 2.23$ | $I_{B2} = 4.46$ |
| B3 (Oil Shale 60 gal/ton) | $\rho_{B3} = 1.7$ | $\alpha_{B3} = 2.0$ | $I_{B3} = 3.4$ |

Again following Terhune, we shall assume that at a distance of 800 meters = 2624 feet from the explosion, the disturbance consists of a spherically symmetric out-going waive whose pressure profile vertically above the source rises from the ambient overburden pressure of 230 bars to a transient maximum of 465 bars. The transient pressure due to the wave itself being 235 bars = 3410 psi. This transient pulse has a duration of about .01 to .02 seconds during which time the pulse

would travel an approximate distance of from 40 to 80 meters. In view of the short duration and spatial extent of this pulse compared with the other dimensions occurring in the problem, it would seem reasonable to assume that ray theory would give a reasonable picture of how the disturbance propagates. Moreover, the stress-strain relation is approximately linear for a stress variation of this amplitude.

Thus we have investigated the propagation of this compressional wave along a narrow tube of rays which, for simplicity, we take to be vertical. Not only is the geometry of the wave simpler when we confine attention to vertical propagation, but the reflection and transmission coefficients for normal incidence are easier to calculate because there is no compressional to shear wave conversion.

Ray theory requires that we take account of geometrical spreading of the rays and keep track of the changes in amplitude at interfaces such as the 1966 foot discontinuity, where we shall need the transmission coefficient, and the free ground surface, where the reflection coefficient is unity with a change of phase so that the rising compression wave is converted there into a tension wave of equal amplitude.

## 2. The Ray Theory Calculations

The calculation of the amplitude of the spherical wave in Shale A is straightforward; it varies inversely as the distance from the shot point. Thus just below the 1966 foot discontinuity, the amplitude of the out-going pressure pulse is

$$\frac{2624 \text{ ft}}{4034 \text{ ft}} \times 3410 \text{ psi} = 2220 \text{ psi} \quad (2.1)$$

Next we need the transmission coefficient T for the stress at normal incidence. This is given by

$$T = \frac{2I_B}{I_A + I_B}$$

Let us denote by $T_0$ the transmission coefficient when Shale BO is used, etc. Then

$$\left.\begin{aligned} T_0 &= 1.0, \\ T_1 &= 0.755, \\ T_2 &= 0.613, \\ T_3 &= 0.503. \end{aligned}\right) \quad (2.2)$$

From (2.1) and (2.2) we may calculate the amplitude of the compression just above the 1966 foot discontinuity. It is $A_0 = 2220 \times T_0$ psi, etc.:

$$\left.\begin{aligned} A_0 &= 2220 \text{ psi}, \\ A_1 &= 1680 \text{ psi}, \\ A_2 &= 1361 \text{ psi}, \\ A_3 &= 1118 \text{ psi}. \end{aligned}\right) \quad (2.3)$$

The New Theory Calculations.

The calculations of the amplitude of the reflected wave in the λ is advanced(retarded) in vertex inversely as the distance from the cone. Thus just below the 1024 foot discontinuity, the amplitude of the cut-going pressure wave is

$$\frac{4\pi\rho c^2 H}{4\pi r^2 \cos\theta} = 3410 \text{ psi} = 2320 \text{ psi} \quad (2.1)$$

Next we need the transmission coefficient T for the stress at the interval boundary. This is given by

$$T = \frac{2\rho_1}{\rho_1 + \rho_2}$$

Let us denote by $T_0$ the transmission coefficient when there is no shock, etc. Then

$$\left.\begin{aligned} T_0 &= 1.0, \\ T_1 &= 0.725, \\ T_2 &= 0.417, \\ T_3 &= 0.372. \end{aligned}\right\} \quad (2.2)$$

From (2.1) and (2.2) we now calculate the amplitude of the pressure wave in the 1024 foot discontinuity. It is $A_0 = 2320 \times T_0$, etc.:

$$\left.\begin{aligned} A_0 &= 2320 \text{ psi}, \\ A_1 &= 1680 \text{ psi}, \\ A_2 &= 968 \text{ psi}, \\ A_3 &= 862 \text{ psi}. \end{aligned}\right\} \quad (2.3)$$

In order to compute the pressure pulse at various depths in Shale B, we must first investigate the way in which the refracted rays diverge above the interface since these rays no longer appear to emanate radially from the shot point. However, they do appear to emanate from an image shot point whose depth may be found as follows:

Let $i$ be the angle of incidence of a ray in Shale A and $r$ be the corresponding angle of refraction in Shale B. Then, if these rays intersect the interface a distance $\underline{a}$ from the vertical (see Figure 2), the distance $\underline{d}$ of the shot point from the interface and $\underline{h}$ the distance of the image point from the interface are related by

$$a = d \tan i = h \tan r \qquad (2.4)$$

Moreover, Snell's law gives

$$\frac{\sin i}{\alpha_A} = \frac{\sin r}{\alpha_B} \qquad (2.5)$$

so that in the limit of small angles

$$\frac{h}{d} = \frac{\tan i}{\tan r} = \frac{\sin i}{\sin r} = \frac{\alpha_A}{\alpha_B} \qquad (2.6)$$

since $d = 4034$ feet, we obtain from Table 1 and (2.6)

$$\left.\begin{aligned} d_o &= 4034 \text{ feet}, \\ d_1 &= 5950 \text{ feet}, \\ d_2 &= 7450 \text{ feet}, \\ d_3 &= 8320 \text{ feet}, \end{aligned}\right) \qquad (2.7)$$

The amplitude of the pressure pulse at various depths in layer B may now be calculated since it varies inversely as the distance from the image shot point (see figure 3).

When the pulse strikes the ground surface it is reflected with a change of phase into a tension wave of equal amplitude. The amplitude of this tension wave continues to obey the same inverse first power law in distance from the image shot point provided that the distance is interpreted as the sum of the depth of the image shot point below the ground surface and the depth of the field point below ground level. This is conveniently represented graphically as in the upper part of figure 3 marked "image space for reflected rays."

## 3. The Results of the Calculations

The amplitudes of the compression pulse and the reflected tension pulse when the upper layer is taken to be Shales BO, B1, B2, and B3 are shown graphically in Figures 4, 5, 6, 7 as functions of depth. The B1 model of Figure 5 is considered to be the most realistic of the four. To the left of the vertical scales in these figures the compressions $-\tau_{zz}$ in the vertical $z$ direction and the compressions $-\tau_{xx}$ in the horizontal directions are plotted as functions of depth. $\tau$ is the stress tensor due to the pressure pulse,

and $\tau_{xx}$ and $\tau_{zz}$ are related by

$$\tau_{xx} = \frac{\sigma}{1-\sigma}\,\tau_{zz}, \qquad (3.1)$$

where $\sigma$ is Poisson's ratio. If, as seems reasonable from experimental data, $\sigma$ is taken to be .3, we obtain

$$\tau_{xx} = .4286\,\tau_{zz}. \qquad (3.2)$$

Actually, the measured values of $\sigma$ vary, but .3 is a reasonable representative average.

In order to obtain the total or net state of stress in the rock as the pulse passes, we need to add the ambient stress to $-\tau_{zz}$ and $-\tau_{xx}$. This is conveniently done by plotting the negatives of the ambient $-\tau_{zz}$, which is the overburden pressure, and the ambient $-\tau_{xx}$ which may be lower than $-\tau_{zz}$. The total $zz$ component of stress will then be represented by the height of the curve $-\tau_{zz}$ above the negative overburden pressure curve. Similarly the total $xx$ component will be represented by the distance between the curve $-\tau_{xx}$ and the one marked ambient horizontal pressure. However, the ambient horizontal pressure is not known accurately and probably varies from point to point in the region of the Piceance Basin. The curve plotted is based upon in situ measurements in the Colony mine.

The difference between the total $\tau_{zz}$ and the total $\tau_{xx}$ will tend to shear the material and in the next section we consider how

this might damage the oil shale formation represented by Shale B in the model.

The overburden pressure is calculated from the densities in Table 1. At a depth of 1000 feet we obtain the following values for the overburden pressure:

| Type of shale | Density in $lb/ft^3$ | Overburden at 1000 ft. |
|---|---|---|
| A | 158 | 1098 psi |
| BO | 158 | 1098 psi |
| B1 | 137 | 952 psi |
| B2 | 125 | 869 psi |
| B3 | 106 | 736 psi |

Now let us consider the part of Figures 4 through 7 to the right of the vertical scale. On this side the amplitudes of the reflected tension wave are plotted. Notice that at depth $z = 0$ the tension wave has the same amplitude as the incident compression and that the tension curves $\tau_{zz}$ and $\tau_{xx}$ continue the compression curves $-\tau_{zz}$ and $-\tau_{xx}$. To obtain the net stresses, we need to substract the overburden pressure or ambient horizontal thrust, as the case may be, instead of adding them. It will be noticed that net tensions in the $zz$ component penetrate in all models up to depths between 1100 and 1200 feet. Even the $\tau_{xx}$ carried by the re-

flected wave exceeds the overburden pressure down to about 500 feet and net tensions in this component may penetrate much deeper if the ambient horizontal thrusts are significantly less than the overburden, as measurements taken in the Colony mine would suggest. At the point where the measurements were taken it was found that the principal stresses were -1078 psi approximately vertical, -276 and -174 psi nearly horizontal.

Net tensions, like the principal compressive stress differences, will be considered in the next section as a further cause of damage to the oil shale.

## 4. The Mechanical Condition of the Oil Shale and the Modes of Damage

We have now computed, admittedly in a simple manner, the approximate maximum stress amplitudes to which the oil shale will be subjected as the compression wave and the reflected tension wave traverse it, at least for that region immediately above the shot point.

Let us consider here the nature of the oil shale, especially its present state of fracture and jointed condition. From experience in the Colony mine it is known that the oil shale contains weak horizontal bedding planes on which there are regions of no cohesion which often contain lenticular pockets of water. These planes are not uniformly weak, but contain areas of low or zero cohesion.

This rock also is transected by numerous joints making various angles up to 54° with the vertical, which in the Mahogany Zone are spaced on the average at 3 to 4 feet apart. In the leaner shale the spacing of similar joints is approximately 6 feet. Like the bedding planes, these joints contain areas of no cohesion and areas of low cohesion (a calcite filled joint may have a tensile strength according to the Brazilian test of 250-1000 psi). These joints often terminate in the intact rock, but are often extensive enough to cut right through the pillars which are left standing in the "room-and-pillar" technique which is used to mine the shale.

We have already noted that bedding planes may contain water; so also do many of the joints and there has, in fact, been significant leaching of water soluble minerals such as nahcolite from many of the joints.

We should at this point remind ourselves of Griffith's theory of brittle fracture. He emphasized the fact that when even quite small loads are applied to materials containing cracks (that is, surfaces lacking cohesion) or narrow cavities of approximately planar form, then large stress concentrations build up at the edges of such cracks or cavities. The effect of these high stress concentrations is to extend the existing fracture even though the level of the applied stress may be far below the tensile strength of the intact material.

Similar considerations show that large stress concentrations exist when a material containing fractures undergoes shearing instead of tensile loading, provided that the fracture has low shear strength. This will occur, for instance, when the fracture contains entrapped fluids or when the effective pressure across the faces of the fracture is reduced by fluid under pressure permeating the supposedly porous medium. Sometimes the presence of water acts chemically on a rock so as to weaken it, but this type of weakening is little understood and depends critically upon rock type.

(a) Shear Failure

Let us first consider the possibility of damage to the oil shale by the rising compression wave. Since the material is under an overall compression as this wave passes, the mode of failure, if any, will be a shear induced by the deviator stresses, i.e. the deviations of the stress field from hydrostatic.

Figure 8 shows a Mohr diagram drawn for the case BO, that is, when the layer of Shale B is of the same material as Shale A, and under the assumption of ambient hydrostatic stress field ($\tau_{xx} = \tau_{zz}$). The larger circles to the right represent the state of stress as the pressure wave traverses the deeper regions (down to 3000 feet). The circle at the extreme left representing the state of stress in the incident wave at the ground surface does not

give a valid impression because the interference of the reflected and incident fields has not been taken into account. The other circles represent the state of stress at depths of 200 feet, 400 feet, etc. down to 3000 feet.

The lines labeled crushed shale represent a Mohr envelope for that material deduced from Terhune 1971. It corresponds to no cohesive strength and a coefficient of friction of .5, which, incidentally, are the lowest values of these parameters for any rock listed by Handin (1966, Table 11-4).

The fact that the circles all lie within the sector bounded by these lines shows that we should not expect further fracturing if the oil shale is dry and the ambient stress is hydrostatic, even though the rock is highly jointed already. But many of the joints contain water and the ambient stress may be far from hydrostatic as previously noted. Thus, the compression wave may extend existing joints by shearing, especially if the faces are separated by pockets of entrapped water.

It is interesting to draw circles corresponding to the ambient state of stress mentioned at the end of section 3, assuming both $\tau_{xx}$ and $\tau_{zz}$ vary linearly with depth. One such circle is labeled 1 in figure 9. The others (if drawn for different depths assuming linearity with depth) would all touch the envelope represented by the

two continuous straight lines. It is interesting to notice that the circle for ambient stress in this case falls partially outside the envelope for crushed shale. It should also be noted that the circles corresponding to the transient stress wave do not pass outside the sector bounded by the outer straight lines which touch circle 1. From this we conclude that the deviation of the ambient stress from hydrostatic does not increase the hazard to the rock due to the passage of the compressional wave. The existence of fluid filled joints on the other hand does increase the hazard above that expected for dry rock.

(b) Tensile Failure

Let us now consider the possibility of damage during the passage of the descending tension wave. Figures 4 through 7 show that tensions may exist down to between 1100 and 1200 feet below ground level.

Since this estimate differs so much from Terhune's estimate of about 360 feet, consideration should be given to the reason for this difference.

One basic difference in our assumptions is that Terhune assumed that his layer B had zero tensile strength, whereas in this work we have assumed the surface material will withstand and transmit the reflected tensile wave to weak zones below, where fracture

may take place. Terhune (1971) and Holzer and Emerson (1972) have stated clearly that maximum depth of spall will occur when the material has zero tensile strength (like loose sand, for instance) in a region extending from ground level downwards into the region where no tensions would be expected, other parameters being held constant. This assumption, which seems to have no basis in calculation, appears to be erroneous. In fact, the present calculations indicate that maximum depth of spall would occur at a depth of about 1100 feet if a bedding plane at that depth lacks cohesion while the material above has sufficient tensile strength to transmit net tensions to that depth.

The oil shale in the Piceance Basin is overlain by an inhomogeneous layer of sandstone and while the leaner oil shale above the oil rich Mahogany Zone has shown tensile strengths from 800 psi to 1600 psi across horizontal planes (Agapito private communication), it is not known how strong the surface layer of sandstone is, and its thickness varies from place to place in the Basin.

The effect of low tensile strength in the surface layers down to a depth equal to the pulse length is roughly to clip the amplitude of the descending tension wave to the level at which fracture occurs. Thus on the basis of Figure 5, our most realistic model,

we would predict that if tensions near the surface of about 1200 psi can be supported then net tensions will penetrate to a depth of 1140 feet. If only 500 psi can be supported at the surface, then net tensions will penetrate to about 500 feet. If the surface layer has zero tensile strength, we will obtain spalling at a depth where the reflected tension pulse begins to emerge from the canceling interference of the incident compression pulse. We would then approximately regain Terhune's estimate.

Unfortunately, the relevant data on the tensile strength of the sandstone is lacking. The only sample of this rock known to author was estimated to have a tensile strength of about 500 psi, but it is not known how typical this sample is of that stratum. It appears, then, that to the extent to which the overlying sandstone approximates loose sand, we shall regain Terhune's estimate of depth of spall and, to the extent to which it approximates the mechanical properties of the leaner shale, tensions may penetrate to over 1100 feet and affect the mechanically weak Mahogany Zone.

From these considerations and in view of the lack of data, Terhune's estimate of 360 feet does not seem to be a conservative estimate for the depth to which tensions may be transmitted.

Since these estimates depend critically upon the strength of the upper layer of sandstone, it would be highly desirable for

data concerning this parameter to be gathered as soon as possible.

To return to the mechanism by which the tensile wave can damage the oil shale. This is by the extension of regions of low tensile strength on the bedding planes and joints. Quite small tensions will extend such regions according to Griffiths' theory. Thus any region subjected to net tensions will be subject to damage, that is, its state of fracture and mechanical weakness will certainly be worsened by the passage of a tensile stress wave sufficiently intense to cause net tensions. Indeed, there is experimental evidence that the locked-in stresses are such that when compressions are removed,previously closed joints may open up, even though no net tensions have been applied.

If tensions penetrate as deep as the Mahogany Zone, then this zone will be particularly vulnerable to this kind of damage because of its highly jointed and fractured state and because the leaner shale above it has greater tensile strength. The $\Sigma\Sigma$ component of stress will tend to open and extend fractures on the bedding planes; the $xx$ component will tend to damage the more nearly vertical joints.

5. Conclusions

Damage to the oil shale may be caused by the upward traveling pressure pulse and also by the down-going tension pulse.

Fluid filled joints or fractures would be susceptible to extension by the shearing effect of the ascending pressure wave. The oil shale is highly fractured and jointed and some joints contain water, so that the oil shale will be subject to further damage by this mechanism.

The reflected tension wave may transmit net tensions to depths of 1100 to 1200 feet if the uppermost layer of sandstone can support tensile stresses up to about 1100 psi. If this surface layer lacks all cohesive strength, then tensions may only penetrate to 200 to 300 feet or, as estimated by Terhune (1971), 360 feet.

The strength of this layer of sandstone is not known, but damage by extension of existing areas of weakness is to be expected on bedding planes and on joints in regions where net tensions exist.

Our calculations show that a conservative estimate cannot, on the basis of existing data, rule out tensile damage as deep as 1100 feet. When tensions penetrate so far, the Mahogany Zone is especially vulnerable because it forms a mechanically fragile zone between layers of the lean oil shales which are mechanically stronger.

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Handin, J. (1966) Strength and ductility, in Handbook of Physical Constants, Geol. Soc. Amer. Memoir, 97 Ed. S. P. Clark, Jr. pp. 223-289

Holzer, F. & D. O. Emerson (1971) An investigation into possible effects of Rio Blanco on the overlying shale and mineral deposits, UCRL Draft

Terhune, R. W. (1971) Prediction of spall phenomena and near surface effects for Project Rio Blanco, UCID-15922, Lawrence Radiation Laboratory, UC, Livermore

## LEGENDS FOR FIGURES

Figure 1. This depicts the geometry assumed for the mathematical model. O is ground point zero vertically above the shot point. The model consists of a layer of Shale B 1966 feet thick overlying a half space of Shale A (see Table 1). The shot point is shown at a depth of 6000 feet. The circle centered at that point represents the position of the spherical wave front carrying the pressure pulse when it is taken as input for our subsequent calculations.

Figure 2. This illustrates the calculation of the depth of the image shot point.

Figure 3. This illustrates a narrow cone of rays emanating from the shot point which is refracted into Shale B where it appears to emanate from the image source. The upper zone labeled image space for reflected rays shows the geometrical spreading of the rays reflected from the ground surface (see text).

Figure 4. This figure refers to Shale BO (see Table 1). Although the curves in this figure are continuous across the vertical axis, the regions to the left and to the right have different significance. To the left of the vertical axis are plotted as functions of depth z the peak compressive stress components $-\tau_{zz}$ and $-\tau_{xx}$, which are carried by the ascending compression wave. The total stress in these components is obtained by adding the ambient $-\tau_{zz}$, which is the overburden pressure, or the ambient $-\tau_{xx}$, as the case may be. In the diagram this is represented by the vertical distance between the line marked overburden and the curve $-\tau_{zz}$, or the vertical distance between the line marked ambient horizontal pressure and the curve $-\tau_{xx}$.

To the right of the vertical axis are plotted the peak amplitudes of $\tau_{zz}$ and $\tau_{xx}$ in the descending tension wave. Net tensions in the zz component exist where $\tau_{zz}$ exceeds the overburden pressure. Similarly, in the $xx$ component when $\tau_{xx}$ exceeds the ambient horizontal pressure. The ambient horizontal pressure may vary from place to place in the Piceance Basin.

Figure 5. This has the same significance as Figure 4, but refers to the case where Shale B1 (see Table 1) is taken as the upper layer.

Figure 6. As for Figure 4 but with Shale B2 (see Table 1) as the upper layer.

Figure 7. As for Figure 4 but with Shale B3 (see Table 1) as the upper layer.

Figure 8. This is a Mohr diagram with circles drawn for the peak state of stress as the compression wave traverses the structure when Shale BO=A is used in the model. The circles refer to points in the material at depths 0, 200, 400, ...., 3000 feet, the circles to the left referring to shallower depths. The lines marked "crushed shale" form a Mohr envelope for a weak rock with zero cohesive strength and coefficient of friction .5. The ambient stress field was assumed to be hydrostatic: $-\tau_{xx} = -\tau_{zz}$ = overburden pressure.

Figure 9. A Mohr diagram. The circle marked 1 represents an ambient stress $\tau_{zz}$ =-1078 psi, $\tau_{xx}$ =-174 psi, $\tau_{yy}$ = -276 psi, values measured in the Colony mine. The smallest circle corresponds to the pressure wave at the surface when Shale B3 is used in the model. The largest circle corresponds to the same model at depth 1966 feet in Shale B3.

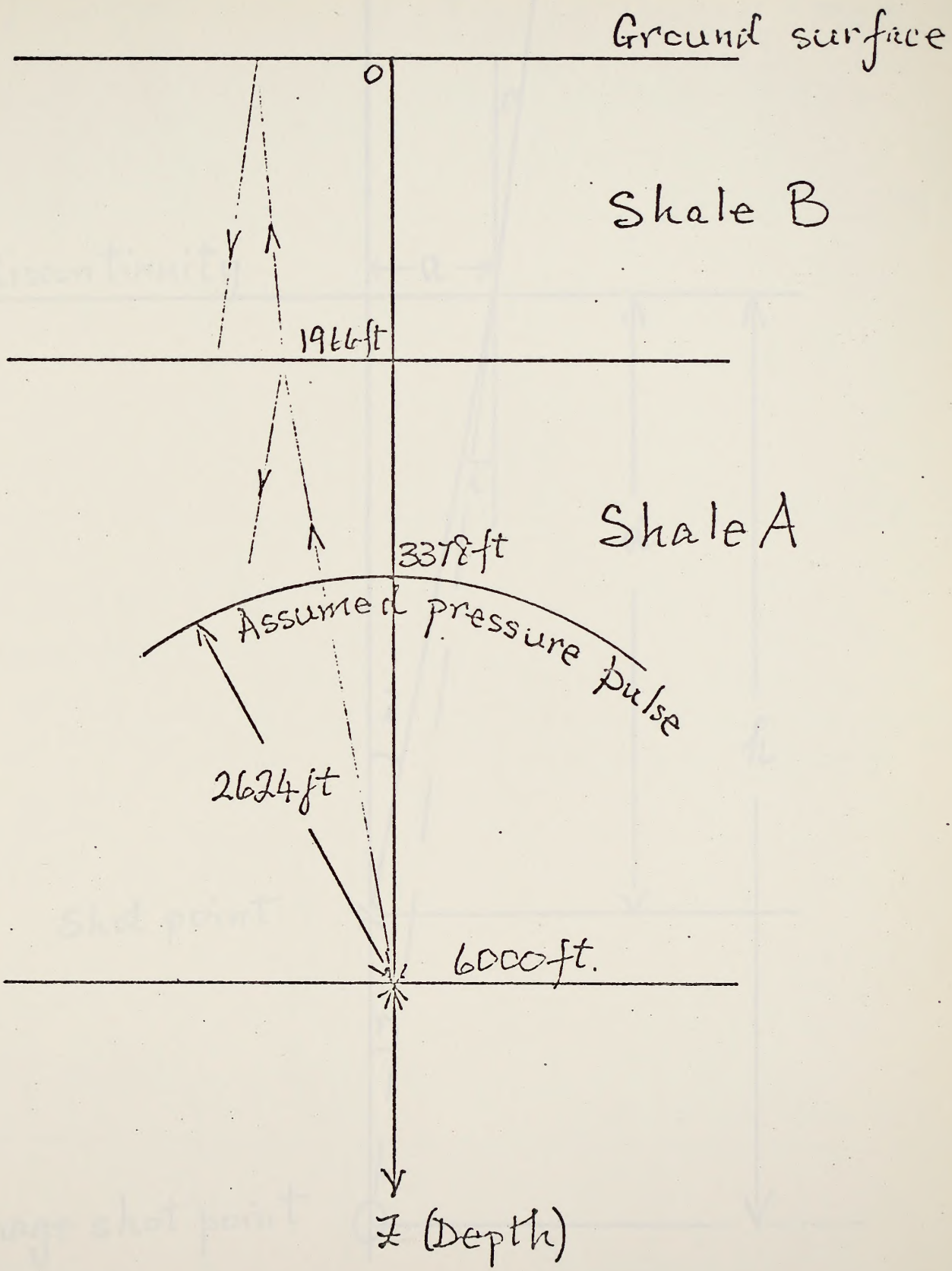
Ground surface
0
Shale B
1966ft
Shale A
3378ft
Assumed pressure pulse
2624ft
6000ft.
Z (Depth)

Figure 1

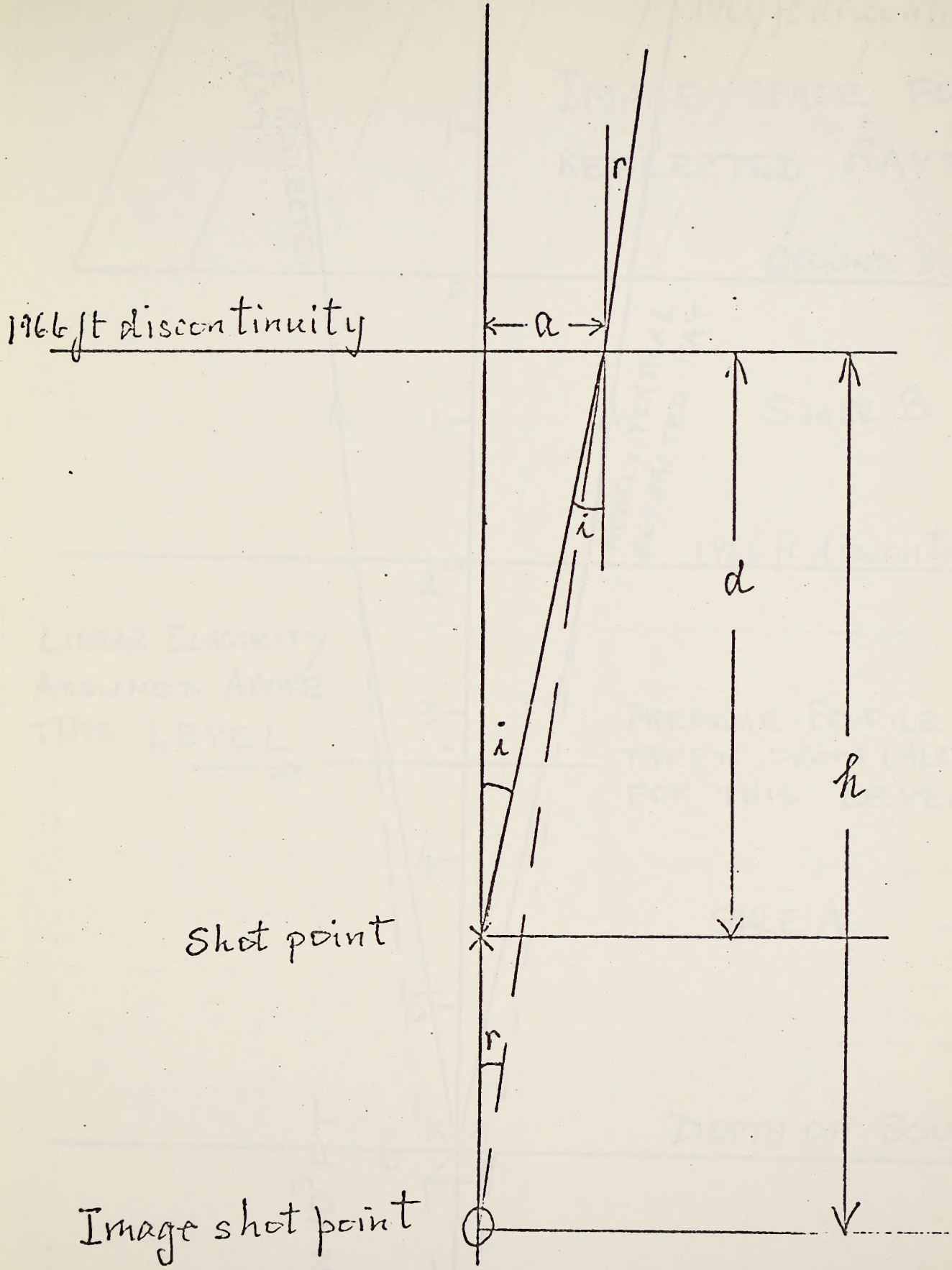


Figure 2

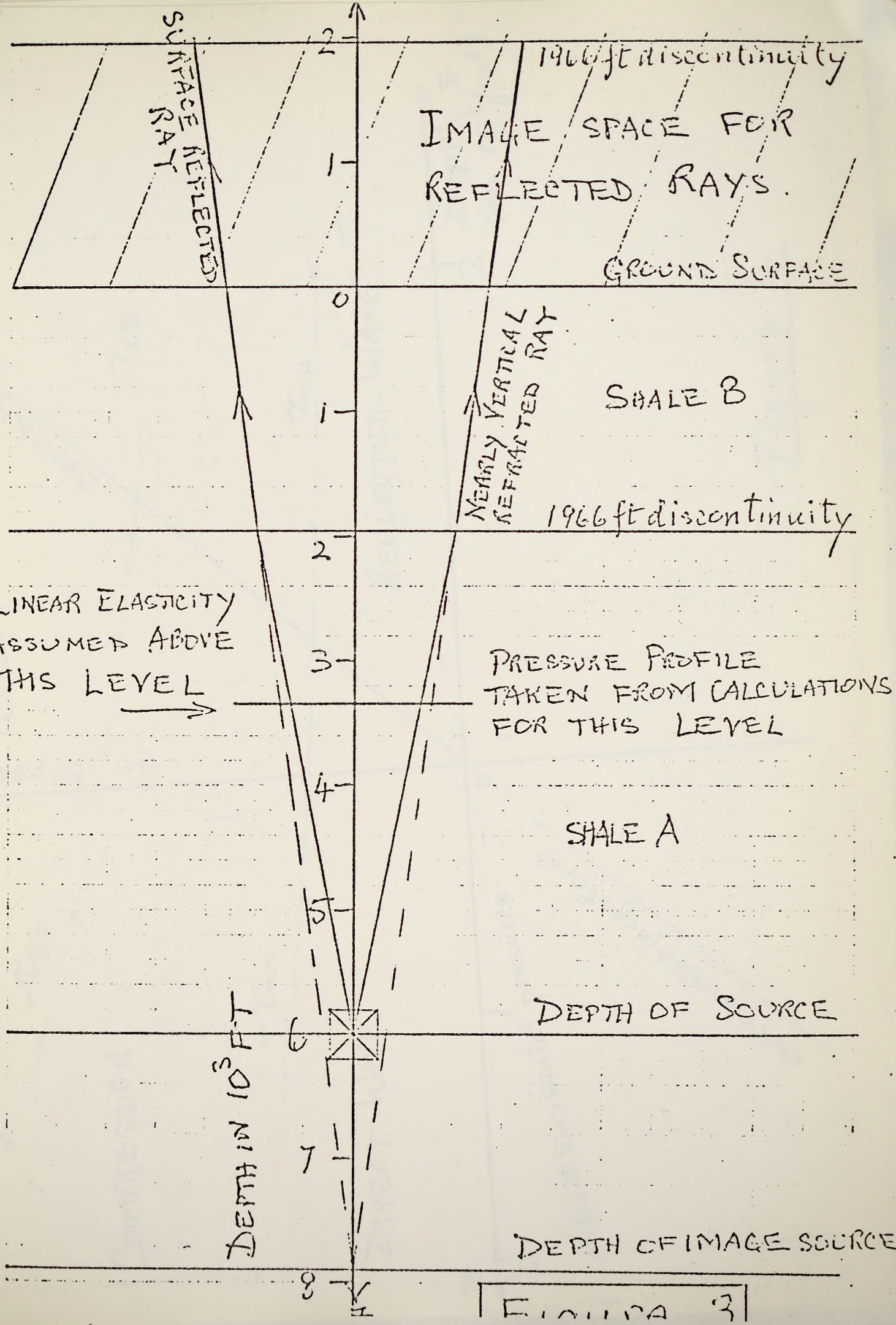
SURFACE REFLECTED RAY
1966 ft discontinuity
IMAGE SPACE FOR REFLECTED RAYS.
GROUND SURFACE
NEARLY VERTICAL REFRACTED RAY
SHALE B
1966 ft discontinuity
LINEAR ELASTICITY ASSUMED ABOVE THIS LEVEL
PRESSURE PROFILE TAKEN FROM CALCULATIONS FOR THIS LEVEL
SHALE A
DEPTH OF SOURCE
DEPTH IN 10S FT
DEPTH OF IMAGE SOURCE
0
1
2
3
4
5
6
7
8

FIGURE 3

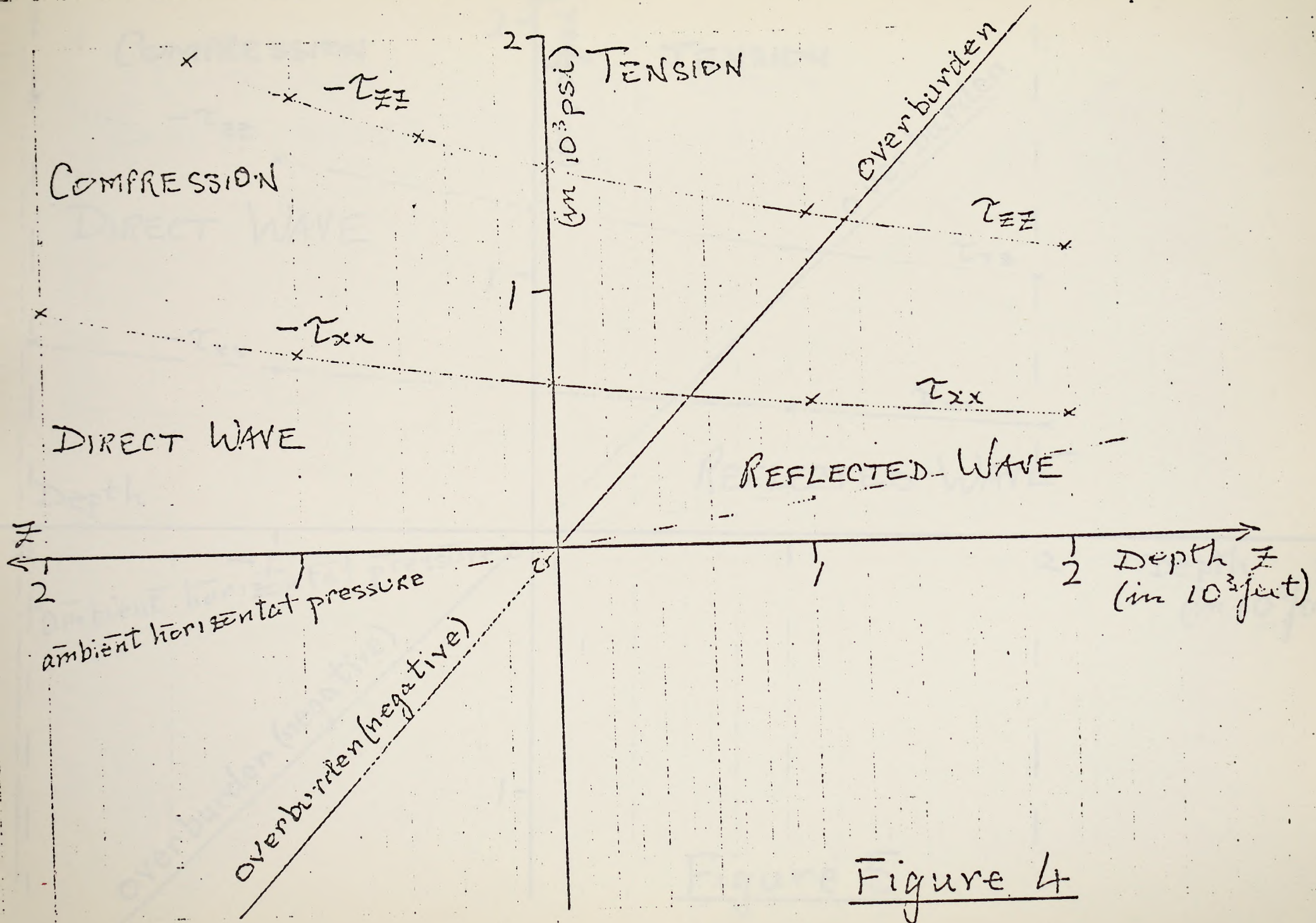
TENSION
COMPRESSION
$-\tau_{zz}$
$\tau_{zz}$
$-\tau_{xx}$
$\tau_{xx}$
(in $10^3$ psi)
2
1
Overburden
DIRECT WAVE
REFLECTED WAVE
Z
2
1
0
1
2
Depth Z
(in $10^3$ feet)
ambient horizontal pressure
overburden (negative)

Figure 4

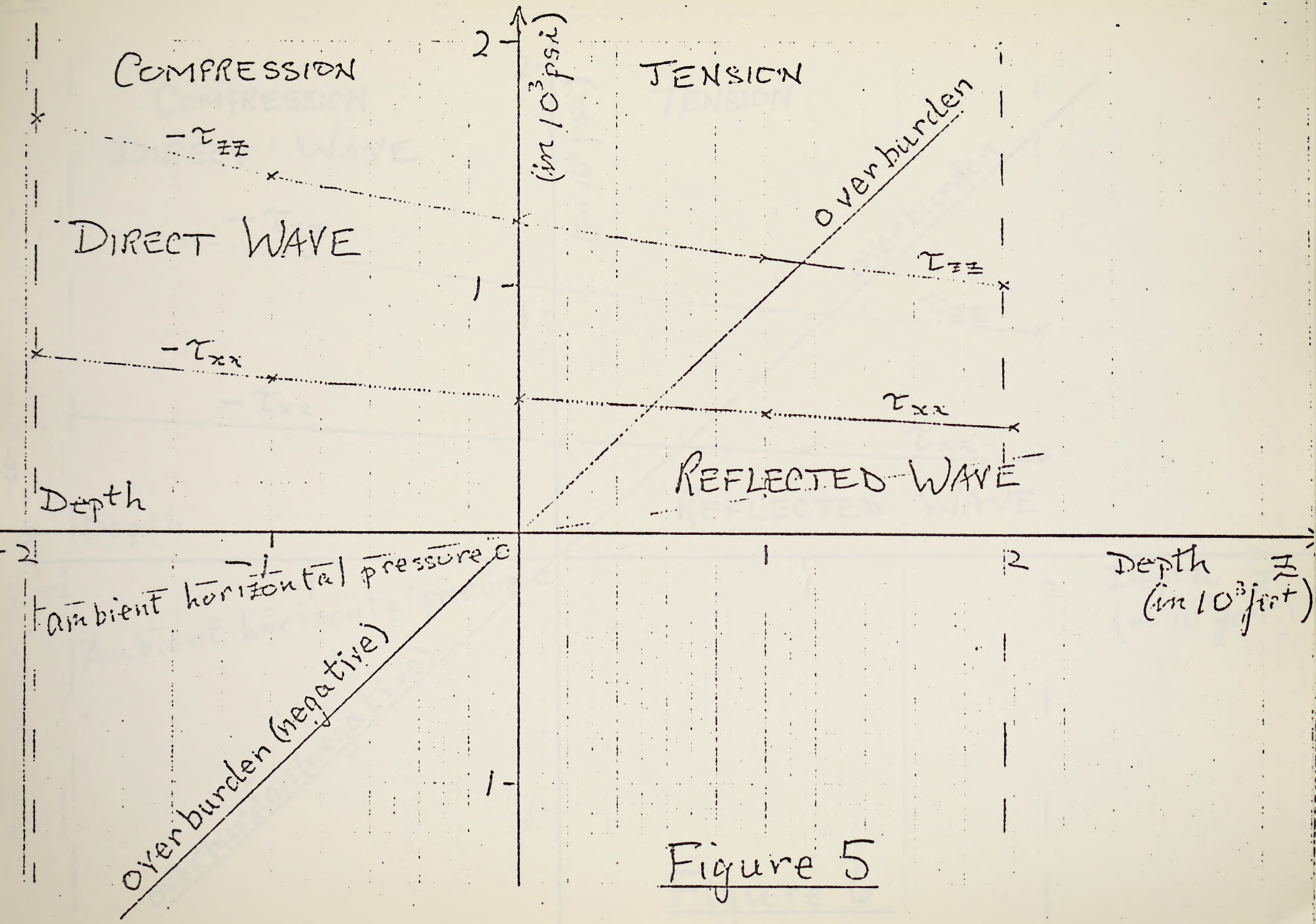
COMPRESSION
TENSION
DIRECT WAVE
REFLECTED WAVE
$-\tau_{zz}$
$\tau_{zz}$
$-\tau_{xx}$
$\tau_{xx}$
overburden
ambient horizontal pressure
overburden (negative)
(in $10^3$ psi)
2
1
1
2
Depth
Depth $z$
(in $10^3$ feet)

Figure 5

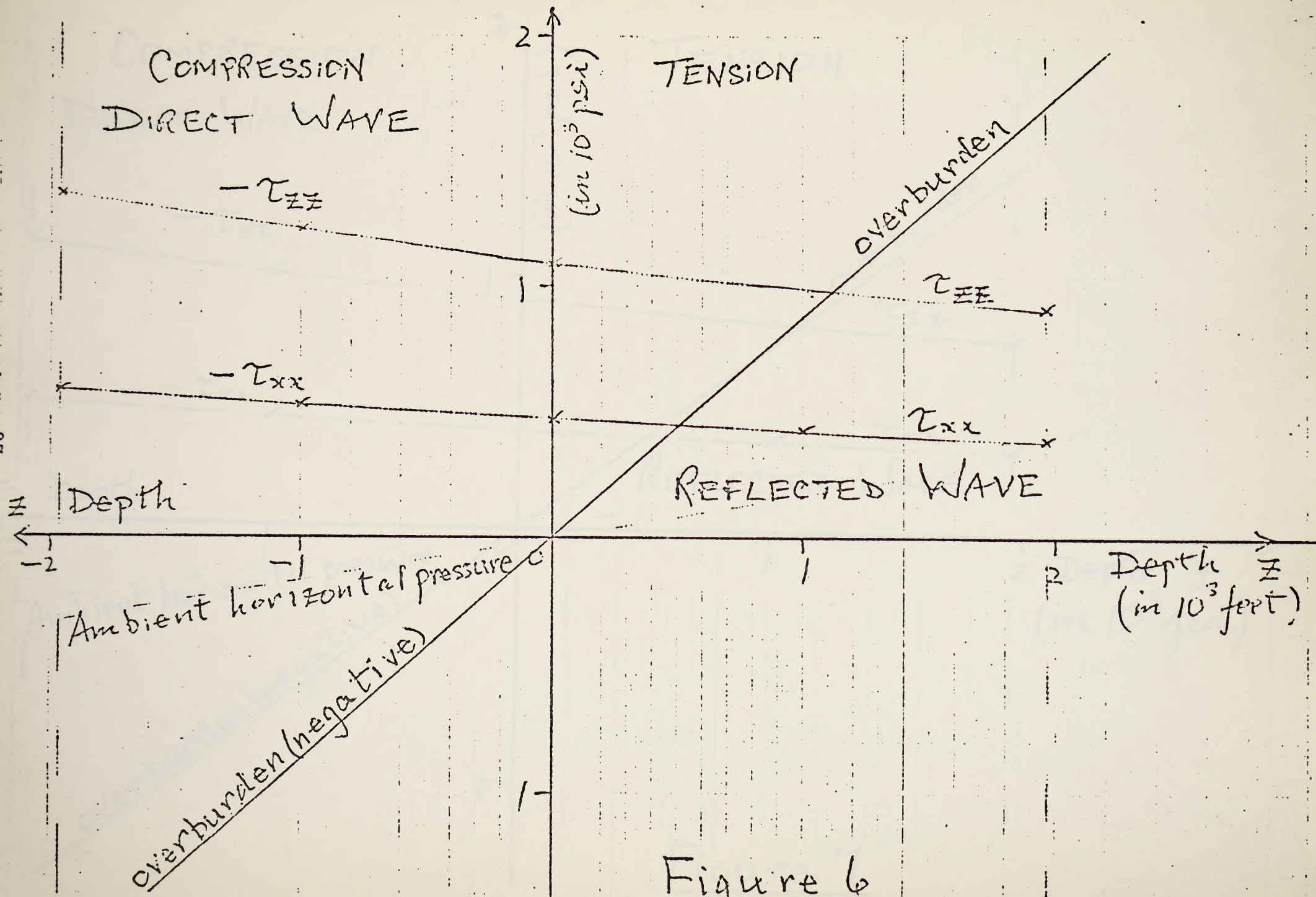
COMPRESSION
DIRECT WAVE
TENSION
REFLECTED WAVE
$-\tau_{zz}$
$\tau_{zz}$
$-\tau_{xx}$
$\tau_{xx}$
overburden
overburden (negative)
Ambient horizontal pressure
Depth z
Depth z (in $10^3$ feet)
(in $10^3$ psi)
2
1
1
-2
-1
0
1
2

Figure 6

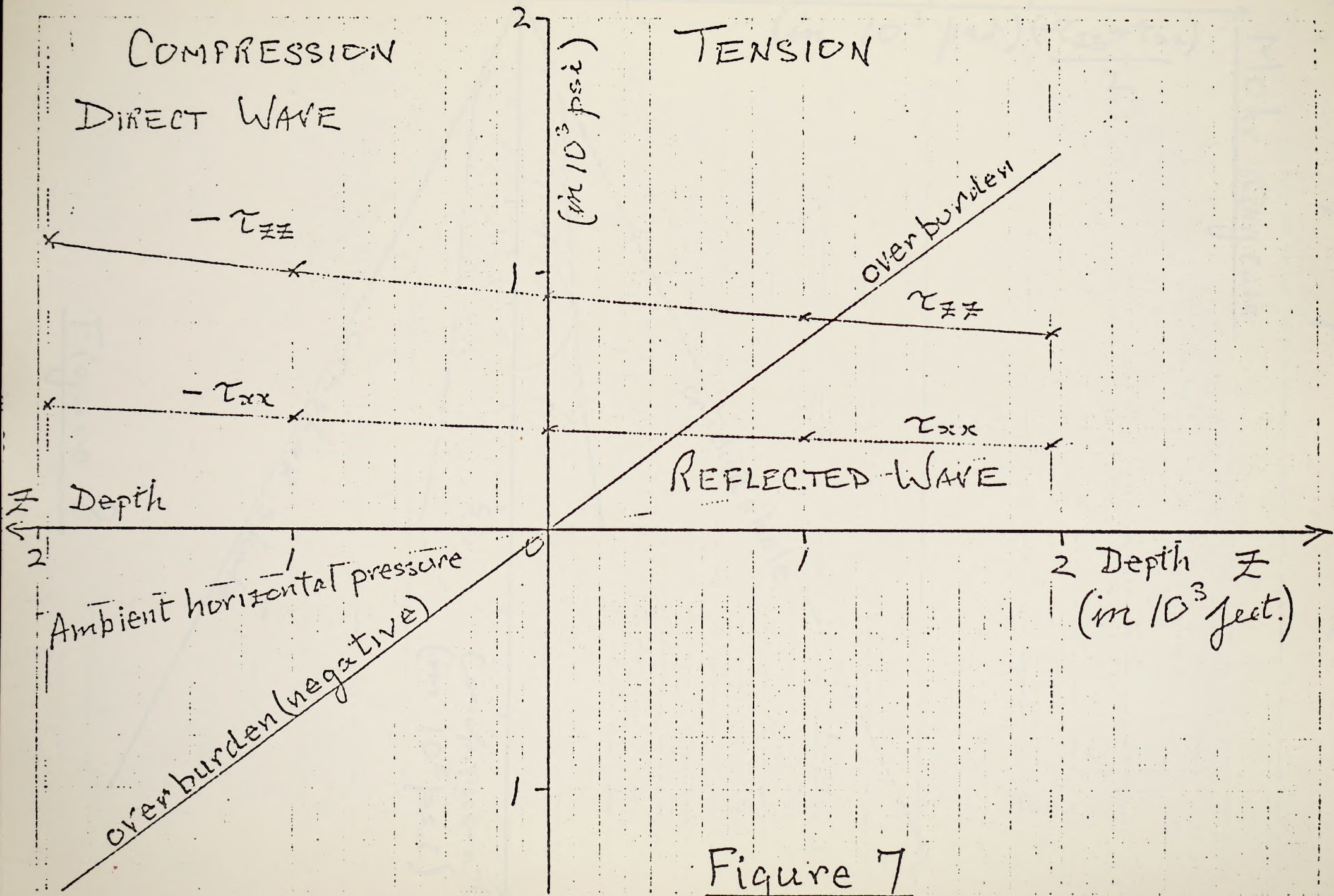
COMPRESSION
DIRECT WAVE
TENSION
(in $10^3$ psi)
2
1
$-\tau_{zz}$
$-\tau_{xx}$
overburden
$\tau_{zz}$
$\tau_{xx}$
REFLECTED WAVE
Z Depth
2
1
0
1
2 Depth Z
(in $10^3$ feet.)
Ambient horizontal pressure
overburden (negative)
1

Figure 7

Mohr diagram for drill trace (for hours 10 to KT

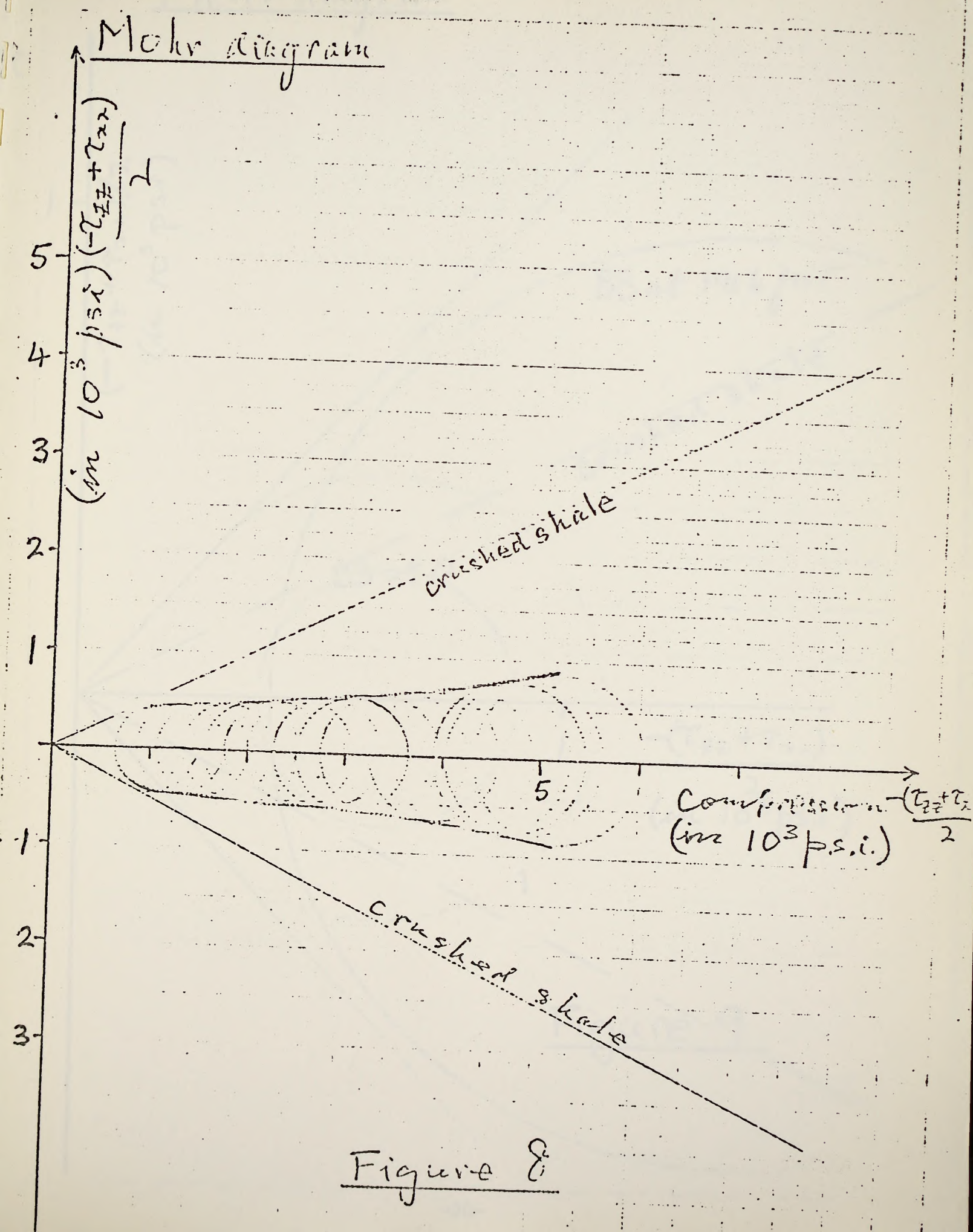


Figure 8

Mohr diagram

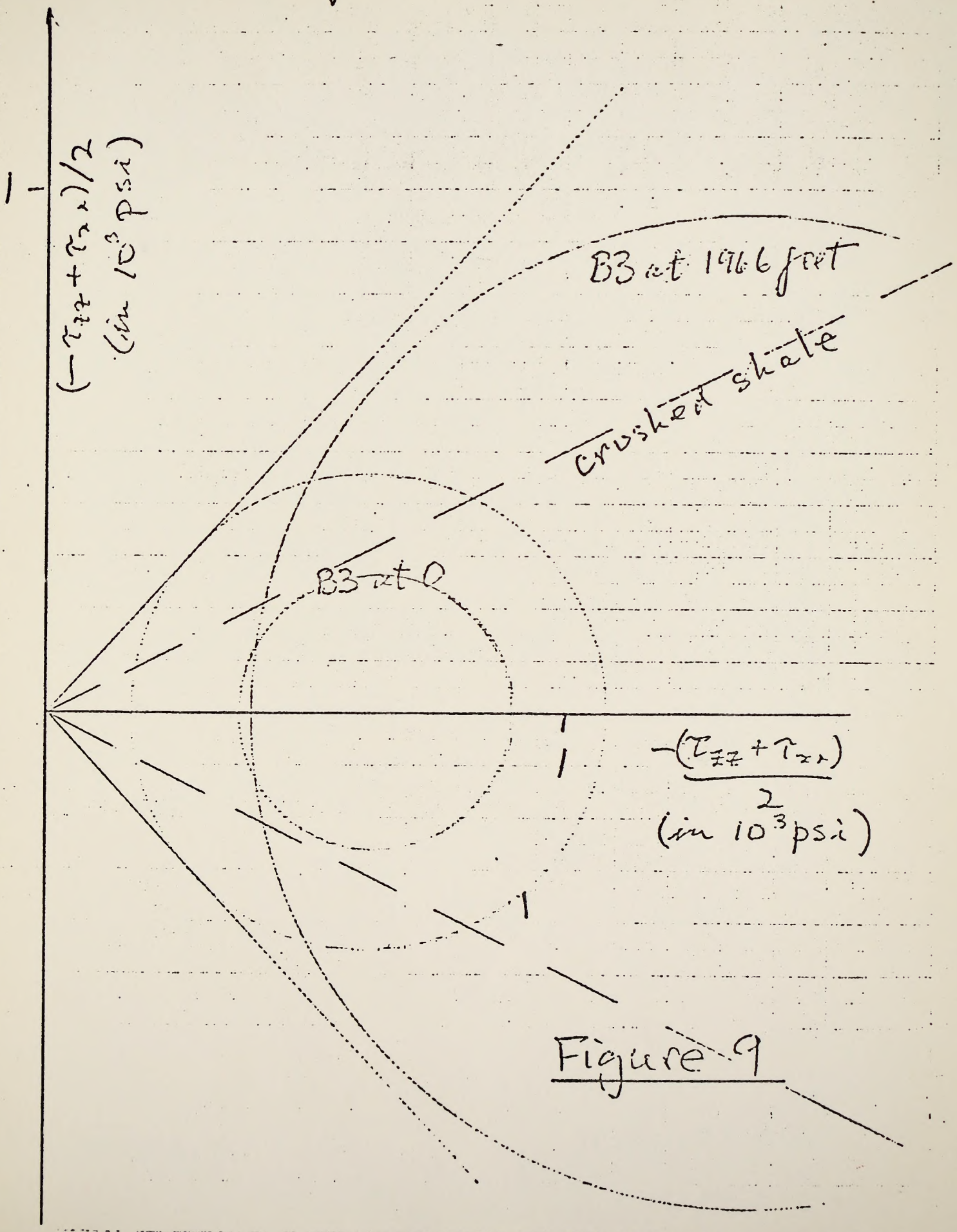


Figure 9

APPENDIX I

# APPENDIX I

## REBUTTAL TO THE REPORT* BY R. BURRIDGE ENTITLED "The Stresses Transmitted to the Rock Formation Overlying the Proposed Rio Blanco Nuclear Shot and Possible Induced Fracture"

by

John Toman
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Livermore, California

The simplified approach used by R. Burridge in his analysis of the possible damaging effects of the Rio Blanco detonation resulted in a conclusion that spall could penetrate to a depth as great as 1200 feet. This is to be compared with the initial LLL (UCID-15922, Terhune) prediction that the spall depth should penetrate no deeper than about 360 feet. The great depth to which Burridge calculates spall is based on two assumptions which we believe to be unrealistic. The first assumption is that peak stresses in the compressive wave decay as $R^{-1}$. The second assumption is that the formation is stronger in tension than the peak tensile stresses developed by the rarefaction wave at all depths until that depth at which the net tensile stress is just slightly greater than lithostatic pressure. At this point, the material is assumed to have zero tensile strength and spall may occur.

The assumption that peak stresses decay as $R^{-1}$ is true only for spherically diverging waves in a perfectly elastic media. Experimentally measured values of attenuation exponents do not exist for the Rio Blanco site. No free field measurements were made during the Rulison test and the data obtained from Gasbuggy is not strictly applicable. The Gasbuggy free field measurements covered a very short range and were too close to the detonation. Extensive measurements of free field motions were made on Amchitka for the Long Shot, Milrow, and Cannikin experiments. Although the geology of Amchitka is quite different than that of the Piceance Basin, a comparison of the physical properties of the rocks at the two locations reveals that the response of these rocks may not be too dissimilar. A plot of particle

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* Referred to in the Transcript of the Informal Public Hearings on Project Rio Blanco conducted by the USAEC at Denver, Colorado, March 27-28, 1972, pp. 156-162, and published in the Exhibits from the Informal Public Hearings on Project Rio Blanco conducted by the USAEC at Denver, Colorado, March 27-28, 1972.

velocity versus scaled range for the Amchitka experiment as determined by Perret* is shown in Figure 1. Stress attenuation will be directly proportional to the particle velocity attenuation which is shown to be $R^{-1.62}$.

For the Rio Blanco location, it is possible to calculate the stress attenuation using the SOC code which calculates the response of rock from first principles. The one-dimensional SOC and the two-dimensional TENSOR codes have been shown to match experimentally derived values extremely well; for example, Terhune has calculated peak particle velocity versus distance for the Wagon Wheel sandstone (UCRL-50993). The equation of state for this rock was determined to be virtually identical to that for the Hoggar granite in which the French conducted a number of nuclear tests. Terhune's calculated particle velocities are in excellent agreement with measured values as shown in Figure 2. The attenuation here is proportional to $R^{-1.6}$. The reported value of $R^{-1.8}$ was subsequently revised to $R^{-1.6}$ by the French as a result of Terhune's observation that the former slope did not appear to be consistent with the measured data. Terhune's calculated accelerations are shown plotted against measured values in the same media in Figure 3. The similar calculations which have been completed using the equation of state and strength properties for the Rio Blanco site indicate an average attenuation proportional to $R^{-1.7}$ and are anticipated to compare well with experimental measurements.

Summarizing the results presented in this analysis, when Burridge's calculational procedure is used with the recently updated value for the Rio Blanco peak vertical overpressure and a more realistic pressure attenuation exponent determined by SOC calculations, the maximum depth of spall is reduced from 1200 ft to 495 feet. Figure 4 compares Burridge's original calculation, curve A, with an updated SOC calculation shown as curve C. Curves B and D are our modifications to Burridge's calculation. For curve B, only the starting peak vertical overpressure was changed. For curve D, the attenuation rate calculated by the SOC code was also included. Prior to discussing the results shown in Figure 4, a brief discussion of the Burridge calculation may be warranted.

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* W. R. Perret, "Cannikin Close-In Ground Motion and the Motion Induced by Milrow," SC-DC-71 4471, Sandia Laboratories, Albuquerque, NM.

The Burridge calculation starts with a peak radial overpressure of 235 bars at 800 meters (2626 feet) from the shot point. These values are taken directly from UCID-15922, Terhune, October 1971. This pressure is then attenuated as $R^{-1}$ to the bottom of the oil shale at a range of 4034 ft (1966 feet below the surface) and results in a stress of 152 bars (2220 psi). Because of an impedance mismatch at this boundary, the transmitted pressure is calculated to be .755 of the incident pressure or 116 bars (1680 psi). This is the first point plotted in compression for curve A in Figure 4. The pressure from here to the ground surface and negative pressures in the rarefaction wave are attenuated as $R^{-1}$ not from the shot point, but from an image shot point located at a depth of 7916 feet. The angle of refraction as the wave enters the oil shale determines the location of the image shot point. Stresses in the rarefaction wave as it descends back toward the shot point are plotted in the quadrant labeled Tension in Figure 4. The difference between the lithostatic pressure and curve A is the total or peak vertical stress at any depth. The intersection of the lithostatic pressure and curve A is the depth at which the net tensions are zero. In Figure 4 this occurs at a depth of 1140 feet. This is the depth which Burridge states is the maximum spall depth.

The calculations completed by Terhune in October 1971 assumed that rock properties at depth were similar to those of Wagon Wheel. Since that time, rock core from the Rio Blanco emplacement well have been obtained and an equation of state developed for the Rio Blanco sandstone. Some changes have also since been made to the experimental model of the SOC code which was used in the initial calculation. The current production model of SOC has been checked against a number of experiments with excellent agreement. With the Rio Blanco rock properties, the current calculations show the peak vertical overpressure at 800 meters from the shot point to be 165 bars rather than 235 bars. This value is consistent in that the Rio Blanco sandstone is not as strong as the Wagon Wheel sandstone and cannot transmit the stress as efficiently. Curve B in Figure 4 shows the changes to curve A which are caused by changing only the starting pressure from 235 bars to 165 bars. The intersection of the lithostatic curve and curve B shows that

the maximum spall depth is reduced to less than 850 feet using the same rationale which establishes the depth at 1140 feet for curve A. Curve C in Figure 4 is a SOC calculation which examines the tensile stresses which would be developed if the rock were artificially assigned a high tensile strength (100 bars or 1450 psi) to prevent it from spalling. The maximum depth of spall for this calculation would then be 550 feet if the tensile strength of the rock at this depth were zero; i.e., if the tensile strength of the rock suddenly dropped from 100 bars to zero at a depth of 550 feet.

Figure 5 is a log-log plot of pressure vs distance from the shot point for the lettered curves shown in Figure 4. The slope of the curves is the attenuation exponent. The SOC-calculated values for the attenuation exponent in curve C is -1.77 to the base of the oil shale and -1.43 through the oil shale to the surface. The slope of Burridge's calculation, curve A, is seen to be -1.00 to the base of the oil shale, but only -0.74 through the oil shale to the ground surface and back. The change in slope from -1.00 to -0.74 is the direct result of using the image shot point to calculate stress attenuation through the oil shale.

Curve D in Figures 4 and 5 differs from curve B in that the attenuation exponent of -1.77 from curve C is used to calculate the stresses over the entire range plotted. It can be seen in Figure 5 that the slope of -1.77 changes to -1.33 for curve D in passing through the oil shale. The reason for this change in slope is the same as for curve A - stresses are attenuated from the image point and not the shot point. The intersection of the lithostatic curve with curve D in Figure 4 occurs at a depth of 495 feet and would be the maximum spall depth using Burridge's method.

The second Burridge assumption in calculating maximum spall depth is that the material is stronger in tension than the peak tensile stresses developed by the rarefaction wave at all depths until that depth at which the net tensile stress is just slightly greater than the lithostatic pressure. At this point, the material is assumed to have zero tensile strength and spall occurs. For this to happen, the material at the ground surface (alluvium and weathered rock) must have a tensile strength in excess of 1200 psi according to Burridge's calculation. At 500 feet below the surface, the

rock must have a tensile strength greater than 700 psi to prevent spall from occurring. These values can be seen in Figure 4 to be merely the difference between the lithostatic curve and curve A at the specified depths.

The effect of varying the tensile strength of the near-surface rock on the maximum depth of spall may be seen in Figure 4. Using curve C as an example, the intersection of the 100, 200, 300, 400, and 500 psi tensile strength lines with this curve results in maximum spall depths of 495, 380, 300, 200, and 100 feet, respectively. These spall depths are to be interpreted as follows: if everywhere between 100 and 550 feet* the strength of the rock is 500 psi (no planes of weakness) the tensile forces in the rarefaction wave will be insufficient to overcome the combined effect of lithostatic pressure plus tensile strength and spall cannot occur. Similarly, if a tensile strength of 200 psi exists between 380 and 550 feet*, then tensile forces in the rarefaction wave are incapable of causing spall below this depth. Hence, the conclusion in this limited interpretation is that the weaker the rock, the greater the depth to which spall may occur. Spalling which takes place prior to reaching the depths outlined above, will, as pointed out by Burridge, reduce the depth to which a specified tensile stress may reach. Another way of stating this is that the tension wave will be attenuated at a faster rate than $R^{-1.43}$ as determined by the SOC calculation.

Meager experimental data are available on measured spall depths from nuclear tests. Table I lists the tests and ranges of measured spall depths. The shot for which the most complete data exists is Milrow. The densities and compressional velocities from the shot point to the ground surface are approximately the same as those measured at the Rio Blanco site. Therefore, the Milrow formation, which is described as a series of volcanic flows, may actually be an experimental model for Rio Blanco. The Milrow explosive was detonated at a depth of 4000 feet with a yield of about 1000 kt (1 MT). The maximum depth of spall as determined by analysis for free fall from acceleration and velocity measurements lies between 500 and 1000 feet below the surface. The reason for this wide range lies in the spacing between instrument packages.

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* Note that the rock strengths assumed for the regions between these depths and the surface cannot increase these calculated spall depths.

An instrument package at 500 feet showed free fall characteristics (spall), while the next instrument at 1000 feet showed only free field characteristics (no spall). A Cliper system (measurement of cable length by time domain reflectometry) indicated a maximum spall depth of 650 feet. A comparison of the yields (1000 vs 100 kt) and depths of burst (4000 vs 6000 ft) between Milrow and Rio Blanco leads to the conclusion that the maximum spall depth for Rio Blanco must be significantly shallower than was observed for Milrow.

A parameter study using the SOC code is continuing at LLL to investigate changes in spall depth resulting from a variation of physical properties. These calculations continue to point toward a maximum spall depth between 300-450 feet. In addition, this one-dimensional code has a built in factor of conservatism in that the tension wave reflected from the free surface converges rather than diverges and results in a greater calculated value for tensile stress than for the actual case of a slightly divergent wave. Another conservative factor is that a point source of 100 kt is assumed for these calculations. Recent studies by F. W. Power,[1] ERC, conclude that the motions at the emplacement well from 3-30 kt explosives detonated simultaneously will be equivalent to about a 44 kt point source. For 50 kt at a depth of 5840 feet, the maximum spall depth ranges between 262 and 374 feet.

With regard to the actual tensile strengths[2] of the various types of rock at the Rio Blanco site, the properties of only three horizons are of interest. The upper ∿ 100 feet at the emplacement well location is alluvium, which cannot be considered to have any significant tensile strength *per se*. Although the Evacuation Creek member of the Green River formation crops out in the vicinity of the emplacement well, at the Rio Blanco site it lies at a depth of between 100 and 400 feet. (Note that the bulk of this member is sandstone, although limestone, marlstone and shale are present). Experience with small, homogeneous samples of sandstone (with no obvious joints or other planes of weakness) indicate widely varying tensile strengths under static loading conditions as noted below:

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1. F. W. Power and S. L. Williams, "Preliminary Considerations of Ground Motion from a Vertically-Oriented Multiple Detonation," Environmental Research Corporation report NVO-1163-227, Nov. 1971.

2. Note that this and the next paragraphs represent a summary of an unpublished memo by C. Boardman (dated June 23, 1972).

| WORKER | TENSILE STRENGTH, psi |
|---|---|
| Chenevert and Gather[1] | 1370 |
| Blair[2] | 280 |
| | 130 |
| | 100 |
| Wuerker[3] | 120 |
| | 230 |
| | 130 |
| | 216 |
| USBM[4] | 180 |
| | 490 |

With regard to the high strength sample listed first in this table, Chenevert and Gather noted that this rock broke easily along bedding planes. The work of Scott[5] and Craft[6] tends to corroborate the generality of this observation; tensile strength across bedding planes, inactive joints and fractures vary from 0 to 200 psi. Thus, the effective strength of the Evacuation Creek member should be considered to be no greater than about 200 psi, with a value of 400 psi assigned for conservatism.

Only two measurements of tensile strength for small specimens are available for Green River oil shale: 450 psi[4] and 1970 psi[1]. Here too, bedding planes, joints and fractures would significantly reduce the *in situ* tensile strength of this member.

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1. M. E. Chenevert and C. Gather, "Mechanical Anisotropies of Laminated Sedimentary Rock," SPE Journal, 1965.
2. B. E. Blair, "Physical Properties of Mine Rock, Part IV," USBM, RI 5244, August 1956.
3. R. C. Wuerker, "Influence of Stress Rate and Other Factors in Strength and Elastic Properties of Rocks," Quarterly of the Colorado School of Mines, Third Symposium on Rock Mechanics, Vol. 54, No. 3, July 1959.
4. USBM RI 5130, "Physical Properties of Mine Rock, Part III," June 1955.
5. J. O. Scott, "The Why and How of Fracturing," Oil and Gas Journal, January 14, 1957.
6. B. C. Craft, "Tensile and Compressive Strength of Some West Texas Producing Horizons," unpublished work at LSU, Baton Rouge, Louisiana.

Thus, it can be seen that the net tensile stresses calculated for these intervals by Burridge significantly exceed (by a factor of at least 3) conservatively estimated in situ strengths for the materials of interest and it appears that these surficial materials would undergo spall.

One additional comment on Burridge's paper concerns the qualitative injection of Griffith's theory as a means of extending fractures by small tensions. Griffith's theory assumes isotropy and completely brittle behavior. The oil shale in question is neither. Griffith's theory does work for biaxial loading in glass for certain values of $\sigma_1$, and $\sigma_3$. It does not work in general for real rocks at pressures corresponding to the depths encountered in Rio Blanco. These conclusions are supported in the following references:

1. Heard, H. C., 1960 GSA Mem. 79, pg. 193.
2. Handin, Heard and Magouirk, JGR, 1967, 72, pg. 611.
3. Jaeger, Cook, Rock Mechanics, Methuen 1969.

In summary, it is believed that the Burridge method for estimating spall depth is a reasonable, albeit simple, procedure if realistic attenuation factors and tensile strengths are assumed. It is unreasonable to assume that the material at the ground surface and in the near surface weathered zone can withstand tensile stresses as large as 1200 psi. This was a necessary ingredient in transmitting the tensile forces of the magnitude calculated by Burridge. The maximum estimated spall depth of 550 feet derived from the LLL SOC calculation is also unrealistic in that spalling was prohibited from taking place in order to calculate the peak tensile stress with depth. Tensile strengths of intact specimens of sandstone, shale, and oil shale are typically less than 500 psi. In a gross sense, the presence of fractures and planes of weakness which certainly exist will further reduce the effective tensile strength of the formation. The effect on spall depth resulting from varying the tensile strength of the rock from zero to some value less than the peak stress at the ground surface is currently being investigated. It is not expected that these depths will vary significantly from the case of zero tensile strength.

TABLE I

SPALL DEPTH DATA

I. Depths From Free Field Data Analysis

| Event | DOB (ft) | Yield (Kt) | Depths at which Separation Due to Spall were Measured (ft)* | | | |
|---|---|---|---|---|---|---|
| Merlin | 972 | 10 | 22,32 | 68,74 | 154,150 | 255,256 |
| Rainier | 896 | 1.7 | 56,75 | ,182 | 240,268 | |
| Milrow | 4000 | ∿ 1000 | 100-300 | 350 | > 500 | |

II. Depths From Free Fall Data Analysis

| | | | Maximum Depths of Spall (ft) |
|---|---|---|---|
| Milrow | 4000 | ∿ 1000 | 500-1000 |

III: Depths From Cliper Data Analysis

| | | | Maximum Depths of Spall (ft)* | |
|---|---|---|---|---|
| Milrow | 4000 | ∿ 1000 | 410 | 650 |
| Jorum | 3900 | " | 400 | |
| Benham | 4700 | " | 250 | |

* Dual numbers i.e., 68,74 indicate that spall was measured to occur in two instrument holes at these depths.

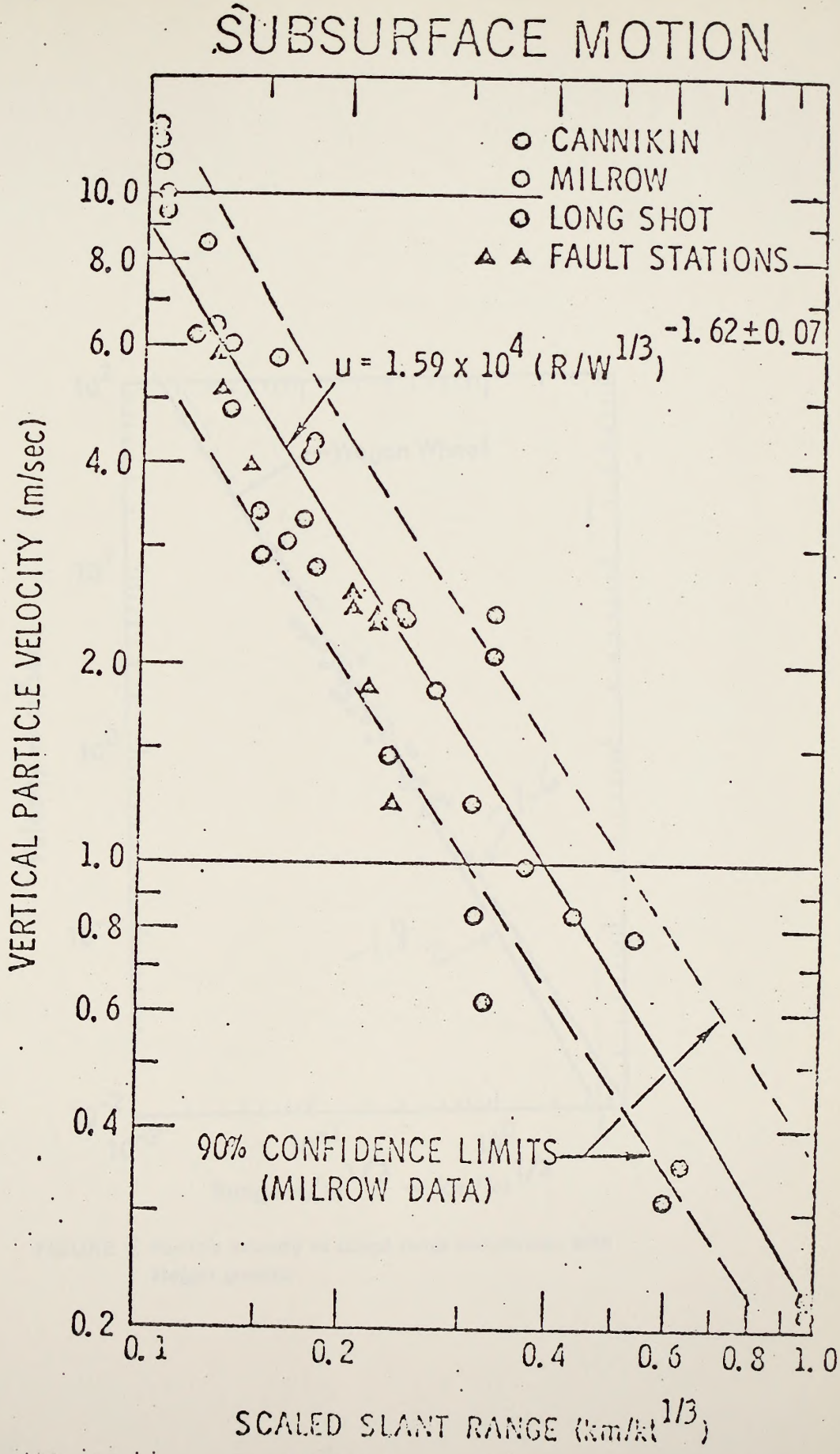


FIGURE I

From W. R. Perret, "Cannikin Close-In Ground Motion and the Motion Induced by Milrow,"SC-DC-71 4471.

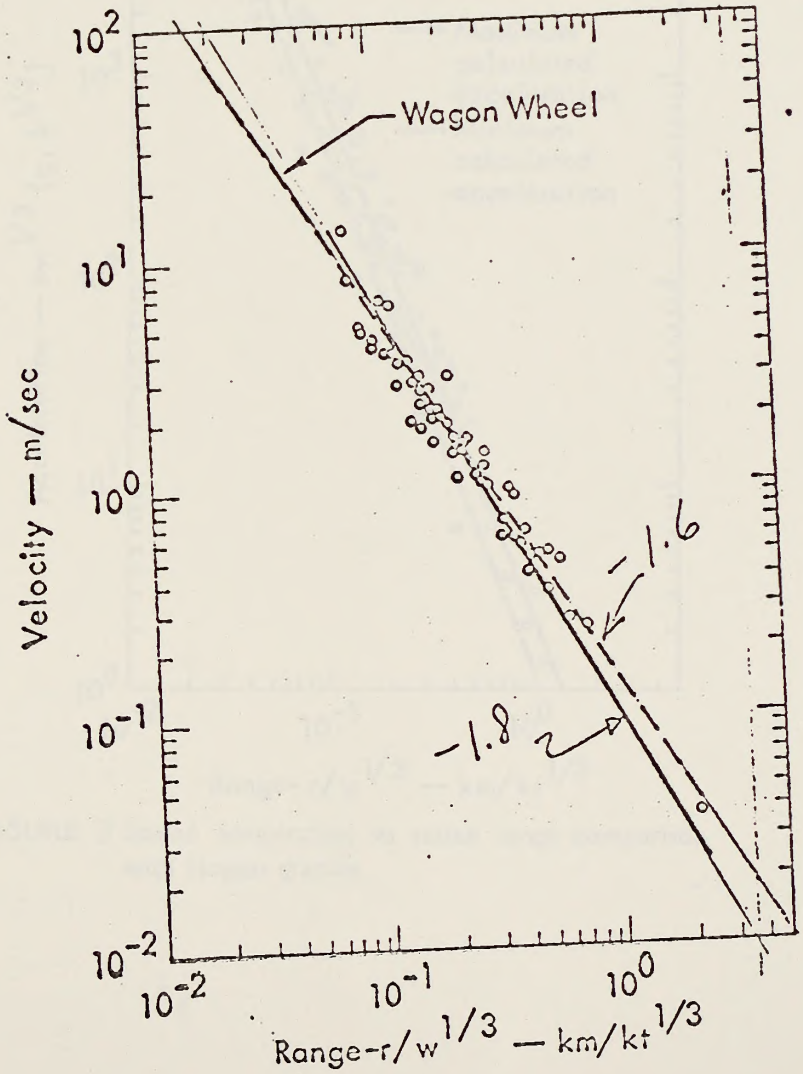


FIGURE 2 Particle velocity vs scaled range comparison with Hoggar granite.

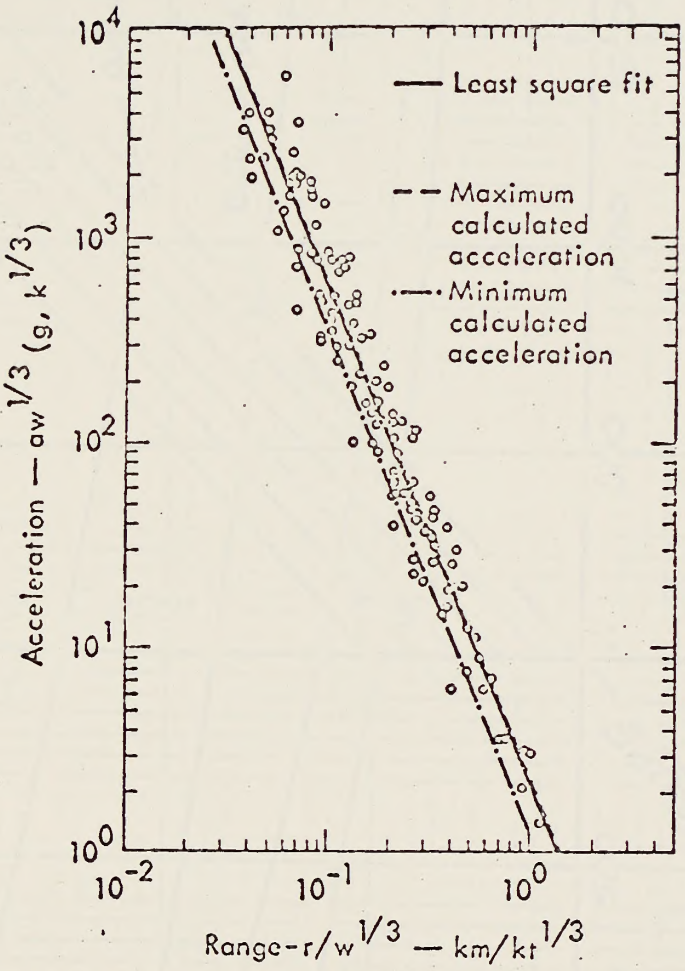


FIGURE 3 Scaled acceleration vs scaled range comparison with Hoggar granite.

GRAPHIC CONTROLS CORPORATION Buffalo, New York Printed in U.S.A. SQUARE 10 X 10 TO THE INCH

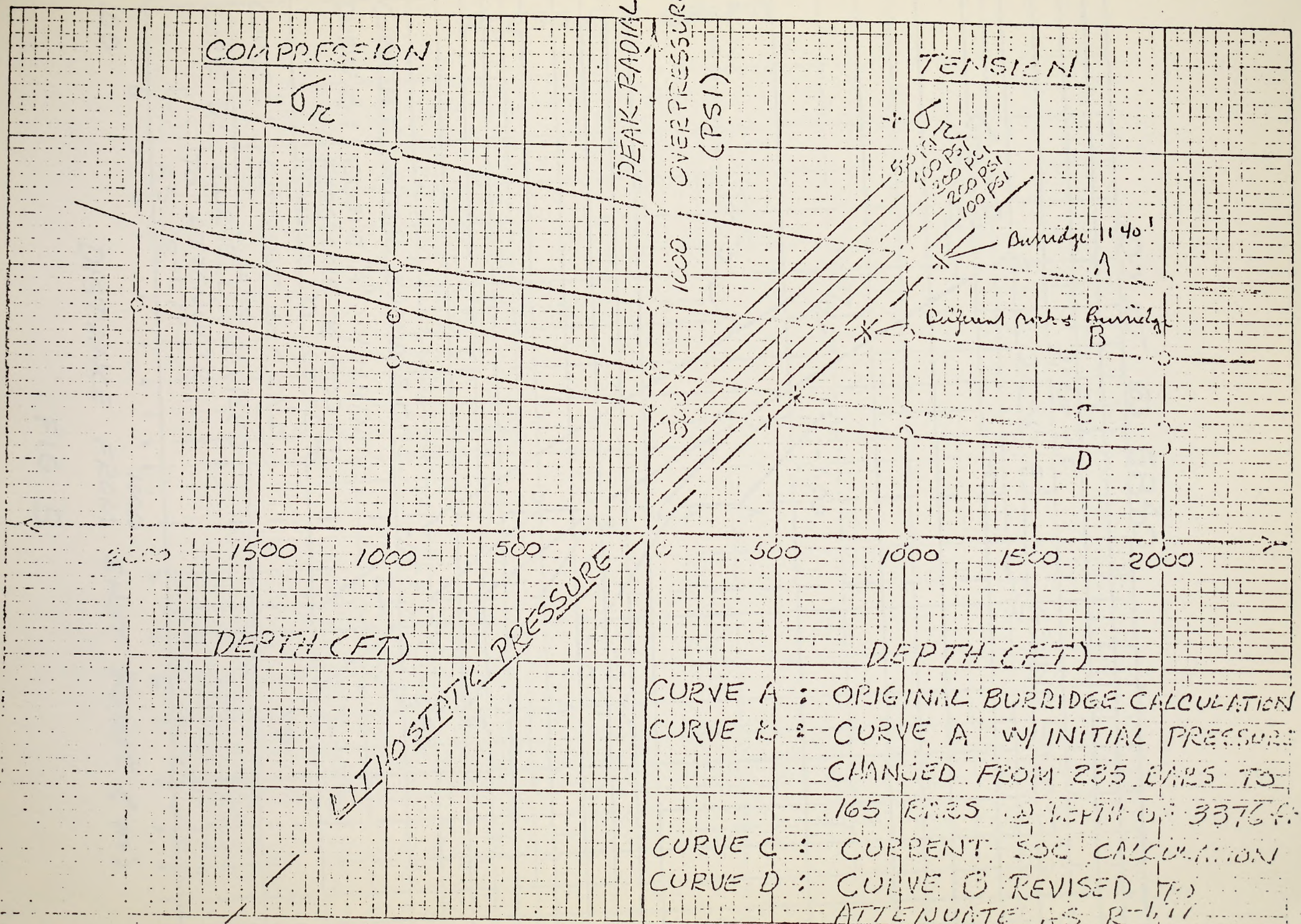


FIG. 4

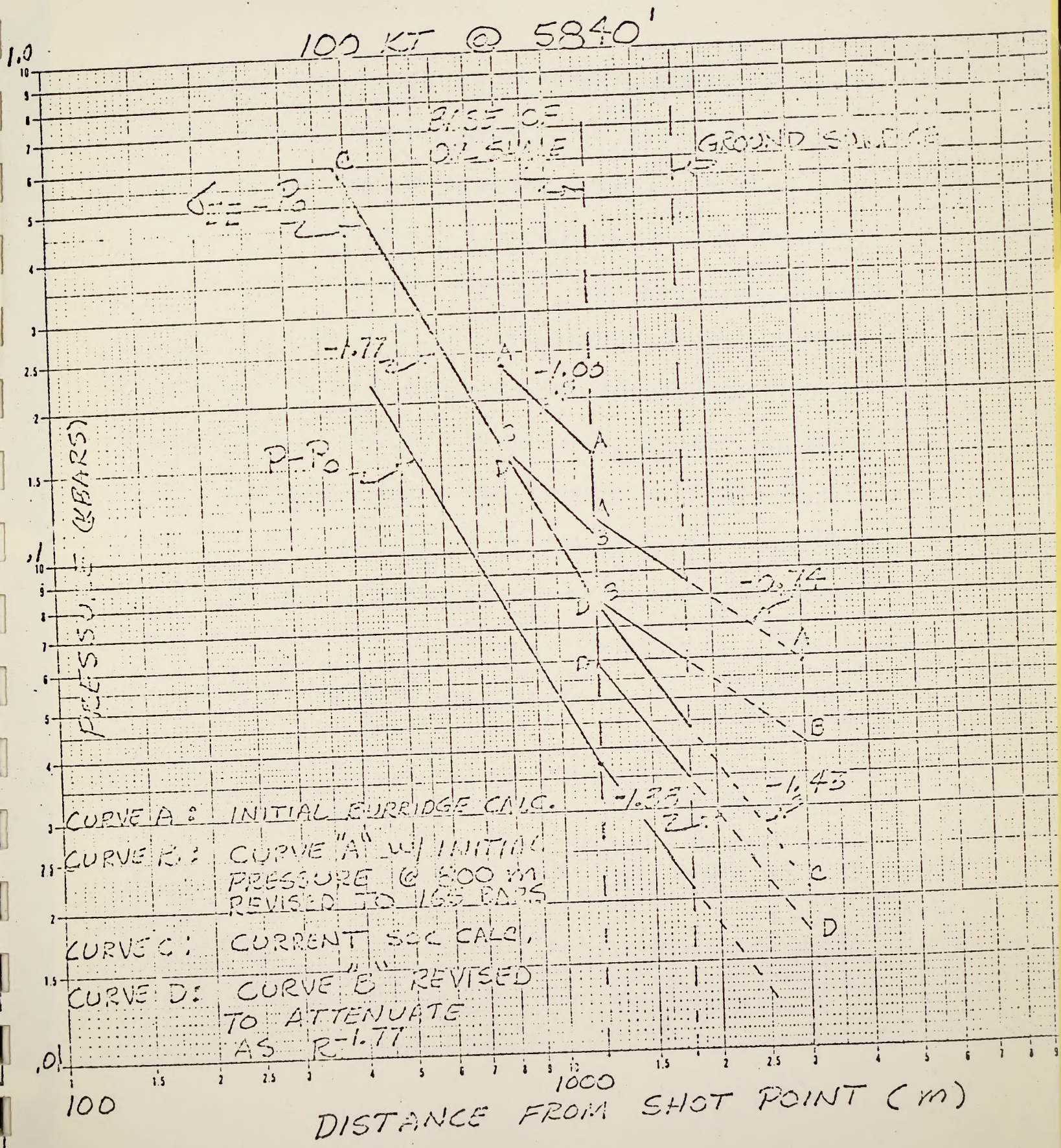
100 KT @ 5840'
BASE OF OVERCAST
GROUND SURFACE
σ = -P₀
P-P₀
-1.77
-1.00
-0.74
-1.45
-1.33
A
B
C
D
PRESSURE (KBARS)
DISTANCE FROM SHOT POINT (m)
100
1000
CURVE A: INITIAL BURRIDGE CALC.
CURVE B: CURVE "A" W/ INITIAL PRESSURE @ 500 m REVISED TO 165 BARS
CURVE C: CURRENT SOC CALC.
CURVE D: CURVE "B" REVISED TO ATTENUATE AS R-1.77

FIG 5

APPENDIX J

## APPENDIX J

## COMPARISON OF DEPTH OF SPALL PREDICTIONS BY TERHUNE, BURRIDGE AND TOMAN

There have been and continue to be considerable differences between the estimates of the depth of spall made by TOSCO's consultants and those made by the project sponsors. The AEC's Environmental Statement predicts a maximum spall depth of 350 to 400 feet based on a paper by Terhune[(a)] (see Appendix F). Terhune in his paper concludes that there is no possible means by which fracturing can occur deeper than 360 feet. TOSCO's consultants, Dames & Moore, reviewed the Terhune work and stated that, because of the uncertainties in making these predictions, a total depth of spall of up to 720 feet would not be unreasonable[(b)] (see Appendix G). Dr. Burridge, an Associate Professor of Mathematics at New York University, was retained by Dames & Moore and estimated that spall could extend to 1200 feet[(c)] (see Appendix H).

(a) Predictions of Spall Phenomena and Near-Surface Effects for Project Rio Blanco, R. W. Terhune, LLL, UCID-15922, October 18, 1971.

(b) Seismic Effects Prediction, Dames & Moore, October 19, 1971 (Appendix G).

(c) The Stresses Transmitted to the Rock Formations Overlying the Proposed Rio Blanco Nuclear Shot and Possible Induced Fracture, R. Burridge, Dames & Moore, March 29, 1972 (Appendix H).

A recent report (July 1972) was prepared by Lawrence Livermore Laboratory on this subject [d] (see Appendix I). This latest report authored by Mr. Toman purports to be a rebuttal to Dr. Burridge. Toman uses a lower value for the pressure of the blast wave than estimated by Terhune and a different value of the attenuation of that wave than used by Burridge. Toman's calculations result in a prediction of 550 feet for the depth of fracturing versus Burridge's estimate of 1200 feet. LLL now discusses the possibility that spall may extend to 550 feet, whereas their previous estimate of 350 feet was reported to be "extremely conservative" at page E-33 of the Environmental Statement.

Burridge pointed out that the assumption that the near surface material has no tensile strength was not a conservative one as asserted by the AEC. The Toman calculation of fracturing to 550 feet is based on the assumption introduced by Burridge that the tensile strength of the rock above the oil shale horizon was sufficient near the surface and continued to be sufficient down to the oil shale horizon so that the tensile wave was not attenuated by spalling of the rock above the oil shale horizon. At 550 feet Toman

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(d) Rebuttal to the Report by R. Burridge, John Toman, LLL, SDK 72-7 (Appendix I).

calculates that tensile failure of rock with zero tensile strength would occur. The difference between the Toman estimate of 550 feet and Burridge's estimate of 1200 feet is due to a difference in the magnitude and attenuation of the pressure waves used.

Toman contends that the spall depth of 550 feet is "unrealistic in that spalling was prohibited from taking place in order to calculate peak tensile stress with depth." Toman's contention is that tensile strengths of the rock overlying the oil shale are typically less than 500 psi, although no data are presented to support the contention. Toman indicates that investigations into the effect on spall depth resulting from varying the strength of the rock are continuing (Appendix I, page 8).

The major differences in assumptions used by estimators of spall depth are summarized below:

| Estimated By | Date of Estimate | Peak Vertical Overpressure[b] at 800 Meters, Bars | Attenuation Varies with $R^x$ where x= | Tensile Strength | Estimated Depth of Spall[c] |
|---|---|---|---|---|---|
| Terhune-LLL[a] | 10/18/71 | 235 | Not reported | Note 1 | 360 feet |
| Burridge-Dames & Moore | 3/29/72 | 235 | -1.0 | Note 2 | 1200 feet |
| Toman-LLL | Received by TOSCO 7/10/72 | 165 | -1.77 | Note 3 | 550 feet |

(a) Estimate referred to in Environmental Statement.

(b) Pressure of blast wave.

(c) Spall occurs when rock at indicated depth has zero tensile strength.

NOTES:

1. Assumed zero tensile strength for rock above the oil shale horizon. As a result the strength of the tensile wave was attenuated in spalling the rock above the oil shale horizon.

2. Assumed that tensile strength of rock above the oil shale horizon was sufficient (1200 psi) near the surface and continued to be sufficient down to the oil shale horizon so that tensile wave was not attenuated in spalling the rock above the oil shale horizon. The strength of the rock within 50 to 100 feet of the surface is not important in this calculation. Its strength can be zero and the 1200 foot result would still be obtained, since this rock is never subjected to the full strength of the tensile wave owing to destructive interference by the direct pressure wave. (Indeed, no tensions can be developed at the surface).

3. Assumed that tensile strength of rock above the oil shale horizon was sufficient (650 psi) near the surface and continued to be sufficient down to the oil shale horizon so that tensile wave was not attenuated in spalling the rock above the oil shale horizon.

It should be noted that Toman has changed the estimate of the peak vertical overpressure (Appendix I, page 2) which has an important effect on estimates of tensile fractures. Toman uses a value 165 bars for the peak vertical overpressure versus 235 bars used by Terhune. Terhune assumed Rio Blanco sandstone properties were the same as Wagon Wheel. This re-estimate is based on actual data for rock properties taken from a single core in the Rio Blanco Unit, which data indicates that Rio Blanco sandstone cannot

transmit the blast stress as efficiently as Wagon Wheel sandstone. Terhune assumed that these rock properties were similar to Wagon Wheel rock properties.

Dr. Burridge has had only a limited time available to review the report by Toman. His comment is that the revised value of 165 bars for the peak vertical overpressure at 800 meters from the shot point appears to be reasonable. Therefore, the value of 850 feet for the maximum spall depth (Toman Figure 4, curve B) which differs from Dr. Burridge's own calculation only in the assumption as to peak vertical overpressure, would also appear to be reasonable. However, as noted above, Dr. Burridge has not had access to the data required to determine the accuracy of the value of 165 bars, which was made on the basis of measurements of rock properties in the emplacement well. There is no basis for believing that normal variations of these properties from place to place in the Unit would not result in estimated peak vertical overpressures either larger or smaller than the revised value used by Toman. Moreover, the report does not reveal the confidence interval for the revised value in the precise location for which it was estimated.

Toman's estimates of spall depths of less than 850 feet result from estimates of the value of the attenuation of the tensile wave which are greater than used by Dr. Burridge. Dr. Burridge has not had an opportunity to examine the basis of Toman's predictions, and therefore has not been able to comment on the reasonableness of the

of the prediction that spall may extend to only 495 or 550 feet as has been calculated by Toman.

It is readily apparent that the estimates of maximum spall depth are subject ot change and are quite dependent on the assumptions made concerning the properties of materials involved as well as on the seismic forces generated. Little is known concerning these factors in the regions of the Fawn Creek Shot, and even less is known about the rock properties in the formations above future shots. For this reason, and because the present calculation techniques only crudely model the actual event, TOSCO regards any of the estimates as only approximate. The widely varying estimates of the various experts point out that the matter of spall predictions in the Rio Blanco Unit has been incompletely studied. Reasonably reliable predictions must be based on more complete basic data and mature calculation procedures.

APPENDIX K

APPENDIX K

# KEY PERSONNEL

DAMES & MOORE

## DAVID J. LEEDS

Engineering Seismology, Soil Dynamics
and Geophysics

Mr. Leeds is a senior seismologist for Dames & Moore. Prior to joining the firm in 1964, he was a lecturer and research engineer on the staff of the University of California at Los Angeles for nine years.

At present Mr. Leeds' work is primarily concerned with prediction of strong-motion earthquake effects on structures founded in different types of soil and rock. These studies have required the development of skills in the recording and interpretation of structural vibration, strong-motion and microground motions. He has had project responsibility for a number of seismic and vibration research investigations at UCLA, the U.S. Coast & Geodetic Survey, Dames & Moore and as an independent consultant. These investigations have been for the location of major aerospace laboratory facilities, dynamic studies of earth filled dams, and forced vibration tests of buildings, dams and large rocket engine test stands. Mr. Leeds has also participated in numerous earthquake investigations for nuclear power plants, ambient background observations at nearly 400 sites in the western United States, and blast monitoring associated with construction, quarrying projects and tunneling.

At UCLA Mr. Leeds taught courses and served as faculty advisor in experimental engineering, properties of engineering materials, and engineering geology and seismology.

In recognition of his contributions in the field of vibration analysis and seismology, he received a commendation from the Director of the Carnegie Institute of Washington. Mr. Leeds is also on the roster for UNESCO Earthquake Investigation Missions, and has received research grants from the California State Division of Architecture for selecting optimum locations for strong-motion earthquake recorders.

Mr. Leeds received a B.A. in geology from the University of Texas in 1939. Since 1955 he has continued his education at UCLA, concentrating on engineering and geophysics. In addition, he has contributed to conferences and university extension courses on such diverse subjects as earthquake and blast effects on structures, modern brick masonry technology, engineering and geological aspects of urban hillside site development, strain gauge techniques, experimental stress analysis for missiles and spacecraft, photoelasticity and strain gauges, and aseismic design of high-rise reinforced concrete buildings.

Shortly after graduation from the University of Texas, Mr. Leeds worked on the Gulf Coast in petroleum exploration. He spent seven years as an exploration geophysicist, conducting both gravity-meter and seismic surveys.

In 1947 he joined the U.S. Coast & Geodetic Survey as a geophysicist in charge of the Los Angeles office of the Seismological Field Survey. In this capacity he investigated strong-motion earthquakes and was responsible for seismograph stations through Southern California and Nevada.

For the past 24 years Mr. Leeds has conducted field investigations of most of the major U.S. and foreign earthquakes. In addition, his travels have permitted him to study the epicentral areas of many major earthquakes which have occurred in the last two centuries. Some of these earthquake site studies are the 1948 Imperial Valley earthquake; 1952 Kern County earthquake; 1957 Mexico City earthquake; 1950 Dixie Valley, Nevada earthquake; 1960 Montana earthquake; 1960 Chile earthquake; 1963 Skopje, Yugoslavia earthquake; 1964 Alaska earthquake; 1967 Venezuela earthquake; and 1968 Iran earthquake. Mr. Leeds has also visited the sites of the 1755 Portugal earthquake; the 1890 Mino-Owari, Japan earthquake; and the 1923 Tokyo earthquake. He was a member of the UNESCO Reconnaissance team to the site of the 1968 Khorasson, Iran earthquake.

Mr. Leeds is a member of Sigma Xi, Earthquake Engineering Research Institute (Newsletter Editor), American Geophysical Union, American Institute of Professional Geologists, American Association of Petroleum Geologists, Association of Engineering Geologists, Seismological Society of America, and the Structural Engineers Association of Southern California. He has served as an officer or on committees of many of these technical societies and boards. As a member of the American Institute of Professional Geologists, Mr. Leeds is Certified Professional Geologist No. 674. He is a registered engineering geologist in the state of California, and the author of many published papers in his field.

◆ ◆ ◆

# CIRRICULUM VITAE

ROBERT BURRIDGE
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King's College, Cambridge, England
B.A. (Cantab) 1959
M.A. (Cantab) 1963
Ph.D. (Cantab) 1963
(Thesis: Reflexion of Elastic Waves in a Solid Sphere)

Specialty:
Applied Mathematics: Wave propagation, Fracture mechanics, Theoretical seismology, Earthquake mechanisms.

Academic Positions:
Research Fellow (of United Kingdom Atomic Energy Authority) working in Department of Applied Math. and Theoretical Physics, Cambridge (1967-71)
Fellow of King's College, Cambridge, 1965-71
Assistant Lecturer, University of Cambridge, 1965-67
Assistant Research Geophysicist, UCLA, 1964-65
Research Fellow, Caltech, 1963-1964

Research:
The attached list of publications indicates areas of research activities.

Consulting:
For Lincoln Laboratories (MIT) Seismic Discrimination group (1970 and 1972). For Dames & Moore to estimate effect upon oil shale of underground nuclear explosions.

Honors:
a) College & Universities
Awarded Exhibition in Mathematics at King's College, Cambridge, 1956.
Awarded Major Scholarship at King's College, Cambridge, 1958.
WRANGLER (1st class) in Mathematical Tripos 1958 (in 2 years instead of the usual 3).
Awarded Research Fellowship by the United Kingdom Atomic Energy Authority (1967).
Elected Fellow of King's College 1965.

b) Professional Honors
Awarded an Adams Prize in the University of Cambridge (1971) for an essay entitled 'The Theory of Earthquake Mechanisms.'

Grants (Partial Listing):
Fulbright Travel Grant 1963-65, for travel from Cambridge to Los Angeles.
Principal Investigator of NSF Grant GA 31570 now in effect at NYU.

Invitations to Learned Societies, etc. (Partial listing):
Invited to give a paper on earthquake mechanisms at the 1971 PENROSE CONFERENCE of the Geological Society of America.
Invited to give a paper on Non-linear theories of fracture at the Royal Society, May 1972.
Invited to give a series of seminars at five California Universities. (UC at San Diego, US at Los Angeles, Caltech, Stanford, and UC Berkeley) April, 1972.
Invited to present a paper at a Symposium on Dynamic waves in Civil Engineering at the University College of Swansea, July, 1970.
Invited to spend one month in each of 1972, 1973 & 1974 at Cambridge University. (An invitation that will probably not be accepted in full).

Publications:
List attached.

# PUBLICATIONS

## ROBERT BURRIDGE

1. "The reflexion of high-frequency sound in a liquid sphere," Proc. Royal Soc., A 270, pp. 144-154 (1962)

2. "The reflexion of a pulse in a solid sphere," Proc. Royal Soc. A 276, pp. 367-400 (1963)

3. "Bodyforce equivalents for seismic dislocations," Bull. Seis. Soc. Amer., 54, pp. 1875-1888 (1964) (with L. Knopoff)

4. "First motions from seismic sources near a free surface," Bull. Seis. Soc. Amer., 54, pp. 1889-1913 (1964) (with E.R. Lapwood & L. Knopoff)

5. "The effect of initial stress or residual stress on elastic energy calculations," Bull. Seis. Soc. Amer., 56, pp. 421-424 (1966) (with L. Knopoff)

6. "The Legendre functions of the second kind with complex argument in the theory of wave propagation," J. Math. Phys., 45, pp. 322-330 (1966)

7. "The singularity on the plane lids of the wave surface of elastic media with cubic symmetry," Quart. J. Mech. Appl. Math., XX, pp. 41-56 (1967)

8. "Model and theoretical seismicity," Bull. Seis. Soc. Amer., 57, pp. 341-371 (1967) (with L. Knopoff)

9. "Lacunas in two-dimensional wave propagation," Proc. Camb. Phil. Soc., 63, pp. 819-825 (1967)

10. "The interface problem in model seismology," Geophysics, XXXIII, pp. 473-480, (1968) (with P. Schwab)

11. "A new look at Lamb's problem," J. Phys. Earth, 16, pp. 169-171 (1968)

12. "Theoretical seismic sources and propagating brittle cracks," J. Phys. Earth, 16, pp. 83-92 (1968)

13. "Spherically symmetric differential equations, the rotation group, and tensor spherical functions," Proc. Camb. Phil. Soc., 65, pp. 157-175 (1969)

14. "The self-similar problem of the expanding elliptical crack in an anisotropic solid," Proc. Camb. Phil. Soc., 66, pp. 443-468 (1969) (with J.R. Willis)

15. "A physical basis for earthquake statistics," Publications of the Dominion Observatory, Ottawa, XXXVII, No. 7, pp. 224-234 (1969) (with L. Knopoff and C. Y. King)

16. "The directions in which Rayleigh waves may be propagated on crystals," Quart. J. Mech. Appl. Math., XXIII, pp. 217 - 224 (1970)

17. "The numerical solution of certain integral equations with nonintegrable kernels arising in the theory of crack propagation and elastic wave diffraction," Phil. Trans. Royal Soc., A 265, pp. 353-381 (1969)

18. Contribution to a Discussion on Earthquake Statistics Following the Paper "Stochastic Models for Earthquake Occurrence" by D. Vere-Jones, J. Royal Statist. Soc. B 32, pp. 52-53 (1970).

19. "Seismic radiation and fracture produced wave sources," in Dynamic Waves in Civil Engineering, Ed. D. A. Howells, I. P. Haigh & C. Taylor, Wiley-Interscience (1971).

20. "Lamb's problem for an anisotropic medium," Quart. J. Mech. Appl. Math. XXIV, pp. 81-98 (1971).

21. "Theoretical computations on ridge acoustic surface waves using the finite element method," Electronics Letters, 7, No. 24, pp. 720-722 (1971) (with F. J. Sabina).

22. "The vibration of a whole space and a half space due to the sudden appearance of a crack," Geophys. J. Roy. Astr. Soc. 25, Dec. 1971 (with D. Loewenthall and Z. S. Alterman).

23. "Dynamic shear cracks as models for shallow focus earthquakes," Geophys. J. Roy. Astr. Soc. 25, Dec. 1971 (with G. S. Halliday).

24. "The acoustics of pipe arrays," Geophys. J. Roy. Astr. Soc. 26, pp. 53-70 (1971).

25. "The elastic radiation from an expanding spherical cavity in a prestressed medium," (Submitted Geophys. J. Roy. Astr. Soc. 1971) (with Z. S. Alterman).

26. "The propagation of elastic surface waves guided by ridges," (about to be submitted Proc. Roy. Soc. (London)) (with F. J. Sabina).

27. "Earthquake Mechanisms," an essay (300 pages) which gained the author an Adams Prize in the University of Cambridge (1971).

Form 1279-3
(June 1984)

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Written comment
United States

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